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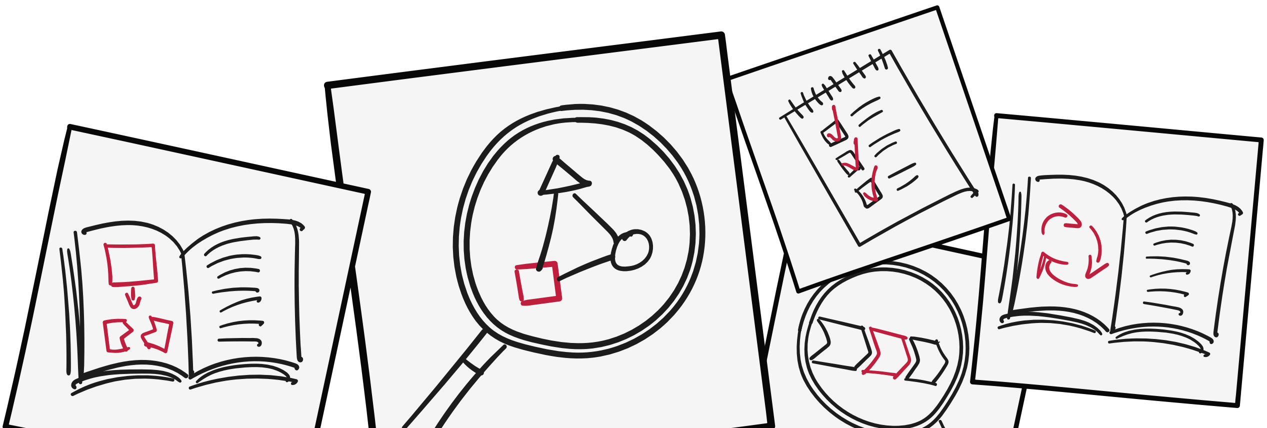
INSTITUT FÜR KONSTRUKTIONSTECHNIK

Timo Richter

A methodical framework supporting product architecture design in conceptualization



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A methodical framework supporting product architecture design in conceptualization

Von der Fakultät für Maschinenbau
der Technischen Universität Carolo-Wilhelmina zu Braunschweig

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genehmigte Dissertation

von:	Timo Michael Gerd Richter
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Braunschweig, November 2019 Timo Richter

Abstract

Product architecture represents the structure of products or product families from different perspectives. By an explicit consideration of product architecture during the design process, the achievement of various design goals can be supported. For this, methodical approaches for product architecture design exist that focus, for instance, on modularization, platform development, or function integration. However, for designers and researchers, the variety of existing approaches causes the challenge to select and apply those approaches most suitable for specific situations in design.

The aim of this thesis is to gain an overarching understanding of approaches for product architecture design. Therefore, existing approaches are analyzed regarding their contributions to different fields of design research, for instance, their proposed product models to represent product architecture and their design principles to improve the product architecture. In this way, the basis for a framework is elaborated that includes and expediently classifies the relevant knowledge from a variety of established approaches. To allow designers to access this knowledge, supports are developed that guide designers through the main activities regarding the consideration of product architecture: first, identifying relevant design goals related to product architecture; second, integrating product architecture design into design processes; and third, determining product architectures according to the defined design goals by the use of principles. The application of the framework is demonstrated by case studies aiming at the conceptualization of product families and improving existing products by considering alternative product architectures.

The results contribute towards both design practice and design research. On the one hand, the framework allows designers to gain a comprehensive understanding of product architecture design and enables them to select and apply approaches most appropriate for their individual design tasks. On the other hand, design research is enriched by an overarching concept of product architecture design allowing researchers to allocate own work in the context of others and elaborate new knowledge on the basis of already existing knowledge.

Kurzfassung

Die Produktarchitektur bildet die Struktur von Produkten und Produktfamilien ab. Durch eine explizite Berücksichtigung der Produktarchitektur während der Produktentwicklung kann die Erreichung von einer Vielzahl von Entwicklungszielen unterstützt werden. Aus diesem Grund existieren methodische Ansätze für die Gestaltung der Produktarchitektur, die beispielsweise auf Modularisierung, Baukastenentwicklung oder Funktionsintegration abzielen. Für Produktentwickler/innen und Forscher/innen ist es allerdings eine Herausforderung, in der Vielzahl bestehender Ansätze die am besten geeigneten für spezifische Entwicklungssituationen auszuwählen und anzuwenden.

Das Ziel dieser Arbeit ist es, ein übergeordnetes Verständnis von Ansätzen zur Gestaltung der Produktarchitektur zu erlangen. Dafür werden existierende Ansätze hinsichtlich ihrer Beiträge zu unterschiedlichen Forschungsfeldern analysiert, zum Beispiel, den vorgeschlagenen Produktmodellen zur Abbildung der Produktarchitektur und den Prinzipien zur Gestaltung der Produktarchitektur. Somit wird die Basis für ein Rahmenwerk geschaffen, welches das relevante Wissen einer Vielzahl etablierter Ansätze umfasst und zweckmäßig klassifiziert. Um Entwickler/innen einen Zugriff auf das Wissen zur ermöglichen, werden Hilfsmittel entwickelt, die sie durch zentrale Aktivitäten der Gestaltung der Produktarchitektur führen: Erstens, die Identifizierung relevanter mit der Produktarchitektur verknüpfter Entwicklungsziele. Zweitens, die Einordnung der Gestaltung der Produktarchitektur in den Entwicklungsprozess. Und drittens, die Festlegung der Produktarchitektur hinsichtlich der definierten Entwicklungsziele durch die Nutzung von Prinzipien. Die Anwendung des Rahmenwerks wird in Fallstudien demonstriert, die auf die Konzeption von Produktfamilien und die Verbesserung bestehender Produkte durch alternative Produktarchitekturen abzielen.

Die Ergebnisse dieser Arbeit leisten sowohl einen Beitrag zur praktischen Produktentwicklung als auch zur Forschung. Einerseits ermöglicht das Rahmenwerk Entwickler/innen ein umfassendes Verständnis von der Gestaltung der Produktarchitektur zu erlangen und ertüchtigt sie, geeignete Ansätze für spezifische Entwicklungssituationen auszuwählen und anzuwenden. Anderseits wird der Stand der Forschung um ein übergeordnetes Konzept für die Gestaltung der Produktarchitektur erweitert, das es Forscher/innen erlaubt, eigene Arbeiten in den Kontext anderer zu setzen und neue Ansätze unter Berücksichtigung von bestehendem Wissen zu erarbeiten.

Contents

1

Introduction

Improving product architecture design

In many situations in product development, designers use representations of the product architecture. Thereby, product architecture allows them to consider the structure of the product under development from different expedient angles, for instance, to evaluate product variety, organization of design processes, or product robustness. However, the variety of specific methodical approaches for product architecture design is large and versatile. In many cases, this results in the challenge for designers as well as researchers to overview the approaches and select those most appropriate for specific design tasks. Therefore, the main objective of this thesis is to gain an overarching understanding of product architecture design to systematize existing approaches within a framework.

To further outline the motivation of this thesis, this chapters introduces the research field of product architecture design. In Sec. 1.1, the theoretical background of product architecture will be outlined, followed by assumptions on needs for research in Sec. 1.2. On this basis, Sec. 1.3 will clarify the objective of this thesis. Finally, Sec. 1.4 will lay out the research approach by formulating three research questions, before Sec. 1.5 will describe the thesis outline.

1.1 Theoretical background

The task of designers is to create products that successfully connect market opportunities, technologies, company's resources, and sales success [AHC15:370]. To evaluate the quality of a product, various properties of a product can be described. Examples for properties are the functionality fulfilled by the product, the product's size and weight, or the costs for manufacturing [Pat82:36f.]. For achieving successful products, designers need to anticipate the required properties and elaborate a design, i.e., a description of the product to be manufactured and offered to customers [Cro07:15f.].

During the design process, challenges for designers arise when a solution for a design task is not obvious, e.g., designers struggle with finding an appropriate design fulfilling the required properties. In that case, designers can use methodical approaches guiding them towards a solution. A key element of those approaches are *product models* that represent the product in a way appropriate for analyzing the properties of the current design and for synthesizing the design in a way that it fulfills the required properties [Lin09:28] [Web07:86ff.]. Since one product model can only represent the product from a specific perspective suitable for a specific design step, in design processes, often various different product models are used [Rot00:54f.] [Buu90:34].

A specific class of product models represent the *product architecture*. In general words, product architecture allows to describe the structure of products from expedient angles [AHM96:17]. Therefore, product architecture can be represented in different ways, for instance, by a function structure representing the functions and their interactions [Sto97:108ff.], by a building structure representing the physical components of a product and their interfaces [EB12:18ff.], or by a combination of both representing allocations between functions and components [Göp98:222ff.]. Thereby, each representation of the product architecture allows to achieve specific design goals, i.e., allows to analyze and synthesize specific product properties like product weight, configurability, or recyclability. In this way, with the product architecture, designers can obtain a design support which serves as a means for considering the product from a perspective suitable for the design goals relevant for them Fig. 1.1.

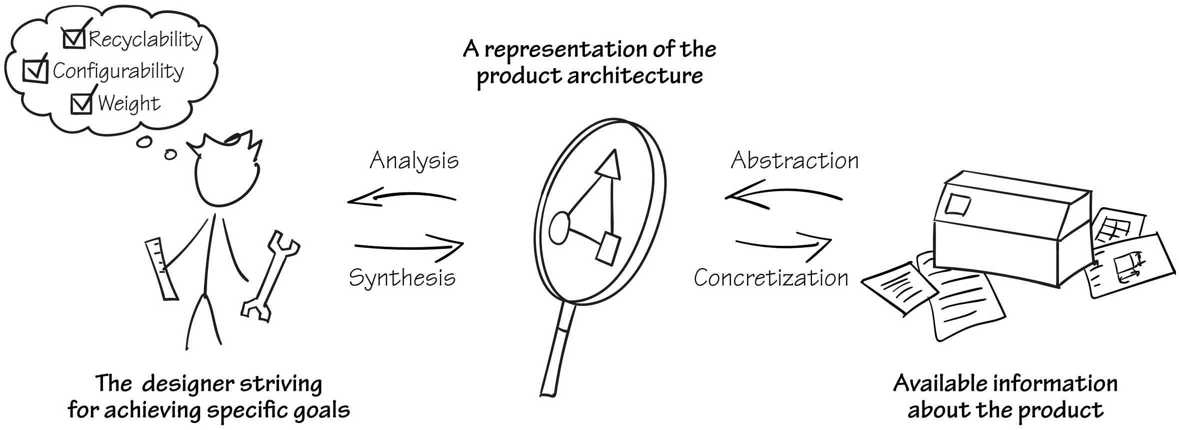


Figure 1.1: Product architecture as a means to represent the structure of a product in an appropriate way for achieving specific design goals

However, the range of design goals that can be addressed by the consideration of product architecture is wide. Therefore, various methodical approaches for product architecture design exist, each comprising a specific viewpoint (e.g., on functions or physical components) and addressing only a limited range of design goals (e.g., reducing weight or increasing configurability). Many of these approaches are associated with terms like platform development, modularization, or function integration, which shall be used here as examples. Thus, approaches for platform development pursue the overarching goal of controlling variety to reduce development effort and manufacturing costs due to scale-effects (e.g., [Ren07], [Har06], and [PBF+07]). Approaches for modularization often widen the focus on strategic goals in various life phases of the product like reducing assembly effort, facilitating repairing, or enabling upgrades (e.g., [Eri98], [Sto97], and [Ble11]). Approaches for function integration rather address physical properties of the product like its robustness, weight, or size and aim at the reduction of the number of parts or the increase of the number of functions fulfilled by a single component (e.g., [Zie12], [KG03], and [KL11]). Often these approaches overlap, and no clear classification can be made. However, for designers, it is important to understand this manifoldness of approaches to be able to identify the most appropriate support for achieving the design goals relevant to their situation.

1.2 Needs for research

In design projects in practice, the author of this thesis has observed various hindering factors for successful product architecture design. Thereby, the identified problem was not that methodical approaches are missing in literature. Rather, it seemed as if the relevance of product architecture is not recognized by designers and existing approaches are not applied properly. According to that, even though design situation exist in that the relevance of product architecture is recognized clearly, for instance, when product platforms are developed. However, in other situations, correlations between product architecture and design goals are ignored, for instance, when a product is modularized based on the consideration of product architecture, but the decrease of robustness due to additional interfaces between modules is not considered.

Based on this observation, as starting point for this thesis, three assumptions are formulated describing the assumed needs for research to be addressed. The three needs concern product architecture design from three different perspectives describing central issues of designers. These are illustrated in Fig. 1.2 and will be described in more detail in the following.

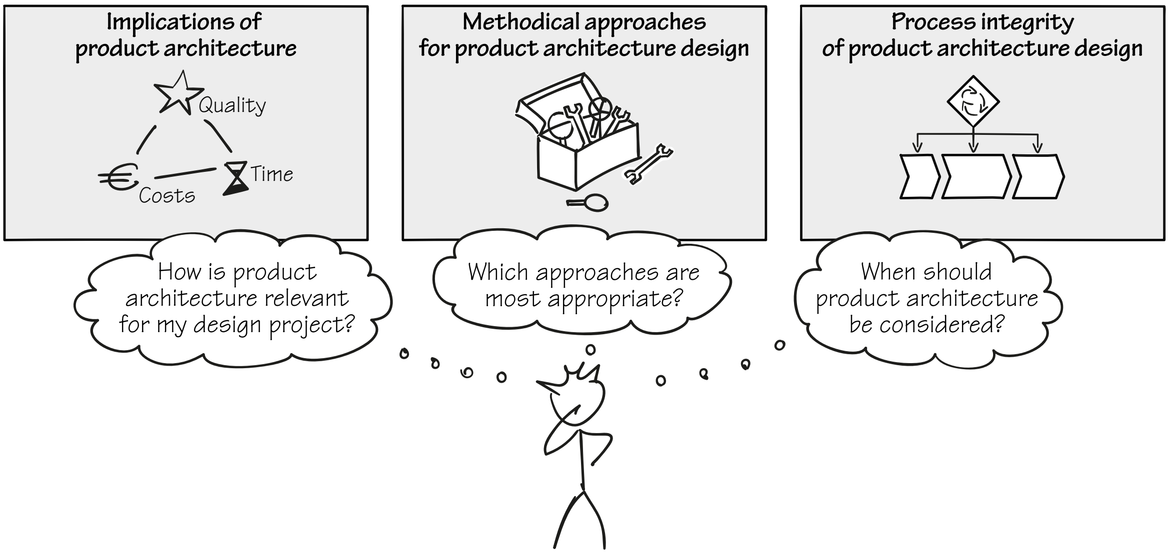


Figure 1.2: Perspectives on product architecture designs describing the needs for research

The first assumption (A-1) regards the *implications of product architecture*, see Fig. 1.2 left. It takes into account the manifoldness of implications and highlights the importance of recognition of these on the success of a design project, for instance, on targets such as quality, costs, and time.

Implications of product architecture

A-1 Product architecture is inherent to each product and has implications on the achievement of various design goals. However, in many cases, designers do not recognize all implications. This impedes the explicit consideration of product architecture regarding the achievement of design goals relevant in specific design projects.

Regarding this assumption, it is presumed that, in many cases, the implications are not known, and the product architecture is not considered when trying to achieve the defined design goals. For instance, the product architecture determines the number of interfaces between components of a product and, therefore, has implications on its robustness. Only when designers understand this correlation, they will consider adapting the product architecture, instead of undertaking less-effective adaptions of the design (e.g., by reinforcing interfaces instead of omitting them). Therefore, this assumption is a prerequisite for the second assumption (A-2) that regards the selection and combination of *methodical approaches for product architecture design*, see Fig. 1.2 middle.

> **Methodical approaches for product architecture design**
>
> **A-2** For product architecture design, various methodical approaches exist that address specific design goals. Each of these approaches comprises an expedient, but limited viewpoint on product architecture design. However, designers often lack an overview of these approaches and are not able to select and apply the approaches most appropriate for specific design situations.

This assumption takes into account that many approaches for product architecture design distinguish themselves in detail by considering different design goals and different representations of the product architecture. Each situation, therefore may require an application of different approaches that need to be identified within the portfolio of existing approaches in literature. The successful application of these approaches, in turn, requires an appropriate integration into the design process. This fact is considered within the third assumption (A-3) on the *process integrity of product architecture design*, see Fig. 1.2 right.

> **Process integrity of product architecture design**
>
> **A-3** The integration of product architecture design into a design process is made by staging, i.e., by selecting and establishing methodical approaches at specific stages of a design process. However, regarding approaches for product architecture design, designers often lack a comprehensive understanding of relevant boundary condition for a most suitable integration. This results, for instance, in a late consideration of product architecture when the freedom of decisions is limited.

This assumption contradicts many established proposals of design processes. For instance, guideline VDI 2221 [VDI93] gives the misleading impression that product architecture design is one specific step within a design process since it defines the determination of modules as only one of seven steps. Within this thesis, it is assumed that product architecture design can contribute to various stages of a design process.

1.3 Research objective and vision

The objective of this thesis builds on the before stated assumptions distinguishing three perspectives on product architecture design. In literature, these three perspectives are well described. For instance, implications of product architecture are described in general (e.g., [PBF+07, UE12, YW07]) or more specific for integration (e.g., [Kol98, US90, Zie12]) or modularization (e.g., [Eri98, Göp98, KBE+14]). For addressing these known implications, various methodical approaches exist, often referred to as *Design for X* methods, for instance, as *Design for Flexibility* (e.g., [FS05]), *Design for Variety* (e.g., [KG18]), or *Design for Manufacturing* (e.g., [Ehr09]). Approaches are even described of how product architecture design can be integrated into design processes, for instance, generally in VDI guidelines (2221 [VDI93] and 2206 [VDI04]) or in specific approaches for the development of modular product families (e.g., [KG18, OHS+16]) or function integration (e.g., [Zie12]).

However, the state of the art in design research only covers fragments of the whole picture of product architecture design. Regarding each perspective, indeed, various specific approaches exist, but in many cases, these are not connected to each other. Furthermore, the different perspectives are not set in relation to each other, although all perspectives are equally essential. For instance, various literature exist aiming at supporting the gathering of implications of product architecture. However, links to methodical approaches to address these implications, or indications when to consider these within the design process are missing. Even though the missing links can be found at other places in literature, the overall picture is not transparent within the current state of the art. Therefore, the objective of this thesis is defined as follows:

Objective of this thesis

The research of this thesis aims at elaborating and sharing a comprehensive understanding of product architecture design by a framework supporting designers in

- recognizing the implications of product architecture on the achievement of design goals,
- selecting and applying approaches for product architecture design on the basis of the design goals defined before, and
- integrating these approaches into design processes properly.

As profiteers of the results of this thesis, designers as well as researchers are considered. Thus, designers shall be enabled to understand all three perspectives on product architecture design to recognize implications, selecting and applying approaches, and integrate these into design processes. For this, an overarching framework shall provide a view on product architecture design from a meta perspective in order to allow to access the fragmented knowledge in existing knowledge in literature. Therefore, the result of this thesis will not be a new design approach in the sense of many other approaches for product architecture design that have a very specific focus. Rather, the result of this thesis shall allow to guide designers through the knowledge already existing to apply it in an appropriate way.

A further target group of this thesis are researchers. They shall benefit from the presented research by gaining a more comprehensive understanding of the situation of designers in product architecture design. The thesis will provide a deeper understanding of designers interacting with the three perspectives. In this way, researchers shall be enabled to classify existing research according to own identified needs for research, and be enhanced in elaborating new approaches by integrating the knowledge structured within this thesis.

1.4 Research approach

To achieve the stated objective, the research approach of this theses will follow established methodologies in design research. The structure is based on the *Design Research Methodology* by Blessing and Chakrabarti [BC09] and will be supplemented by other approaches (e.g., [DA95], [WG01], [PEB+00], and [ESC03]). Accordingly, this research project is performed within four stages:

- Research Clarification (RC),
- Descriptive Study I (DS-I),
- Prescriptive Study I (PS-I), and
- Descriptive Study II (DS-II).

The *Research Clarification* aims at defining goals and focus of research by formulating the initial design problem and research questions. In the *Descriptive Study I*, the design phenomenon is further analyzed in order to increase the understanding of the initial situation and its deficits. This provides the basis for the elaboration of a new design support that is described in the *Prescriptive Study I*. The *Descriptive Study II* outlines the application of the design support in design practice in order to evaluate the improvement.

The results of *Research Clarification* are presented in this section, the other stages will be guided by three Research Questions (RQ), each corresponding to one stage. Thus, for *Descriptive Study I*, RQ-1 is defined in order to increase the understanding of product architecture design in practice and to consolidate the assumed needs described above:

Key Research Question in Descriptive Study I

RQ-1 What factors within a design process influence whether and by which supporting means the product architecture is considered in design practice?

To answer this question, problems in product architecture design will be analyzed on the basis of literature and design projects that were accompanied by the author of this thesis. Therefore, an evaluation of the identified problems will be made within interviews with designers in industry. In this way, a basis is provided for *Prescriptive Study I* guided by RQ-2:

Key Research Question in Prescriptive Study I

RQ-2 How can designers be supported determining the most suitable product architectures?

This question will be answered by formulating five hypotheses on how knowledge regarding product architecture design can be systematized appropriately for enabling designers to access the knowledge within specific design situations. Based on this, a classification of existing approaches for product architecture design will be carried out. The gained knowledge will then be integrated into the framework for product architecture design. Finally, within *Descriptive Study II* the framework will be applied within case studies to answer RQ-3:

Key Research Question in Descriptive Study II

RQ-3 How does the elaborated support improve the determination of product architecture in design practice?

The application of the framework will be shown in two examples. The first example comprises the development of a product platform of industrial products within a medium-sized enterprise. The second example aims at the implementation of Design for Additive Manufacturing into design processes of an automotive company under specific consideration of product architecture. By these two case studies, an initial validation of the results of this thesis can be achieved.

1.5 Thesis outline

The structure of this thesis follows the described research approach. Therefore, it is subdivided into eight chapters of which each is allocated to one of the stages of the *Design Research Methodology*, see Fig. 1.3 left. In addition to this vertical structure of the thesis, a second horizontal structure is laid onto some of the chapters to create an overarching chapter sectioning. By this, the recognition of correlations between the chapters shall be facilitated. This horizontal structure is leaned from an extended model of design research after Hubka and Schregenberger [HS88:109ff.] and comprises five fields of design research as illustrated in Fig. 1.3 as vertical columns.

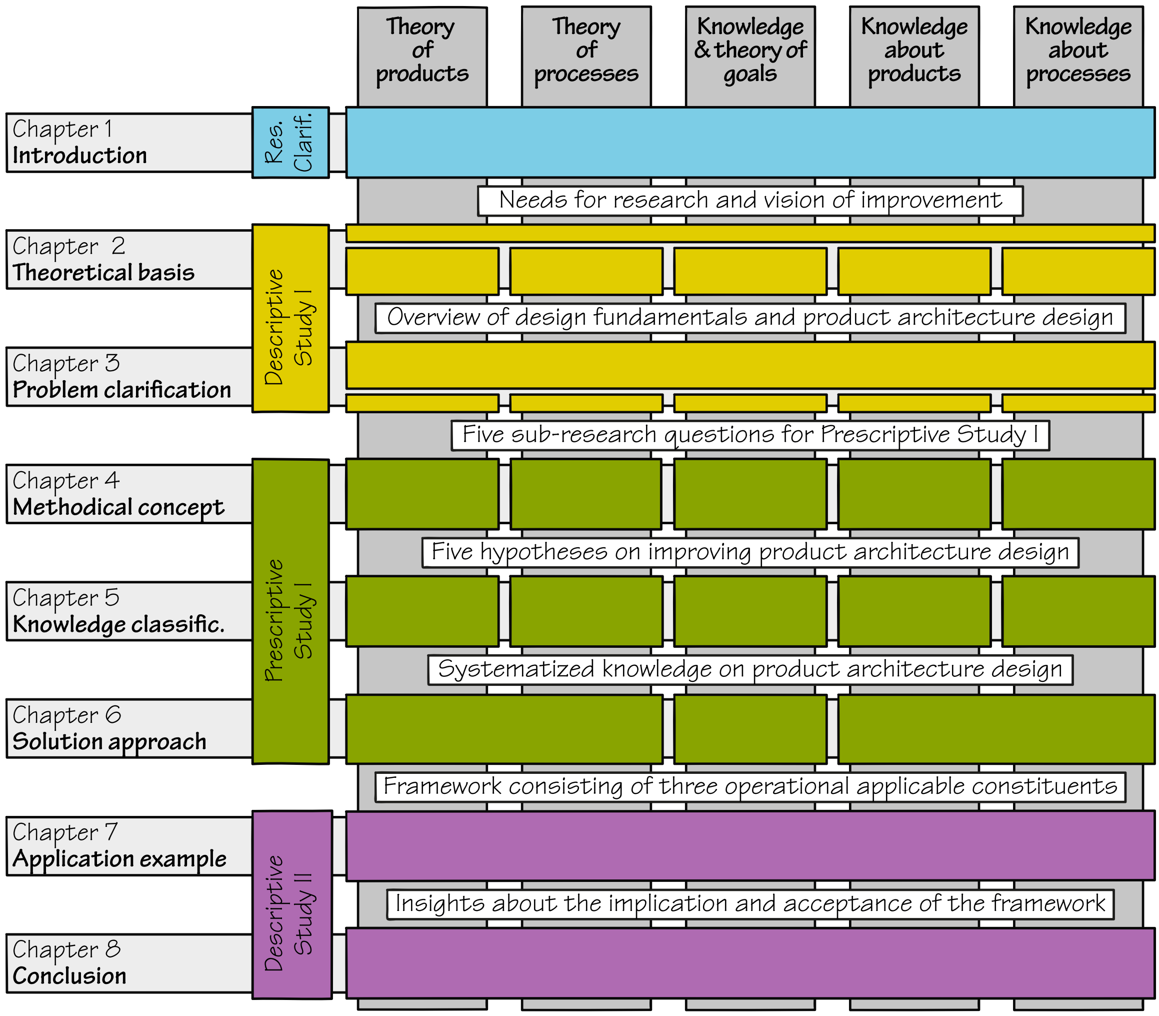


Figure 1.3: Structure of this thesis

The five fields of design research will be introduced in Sec. 2.1.3 in detail, at this point they will only be described in short:

- Theory of products
- Theory of design processes

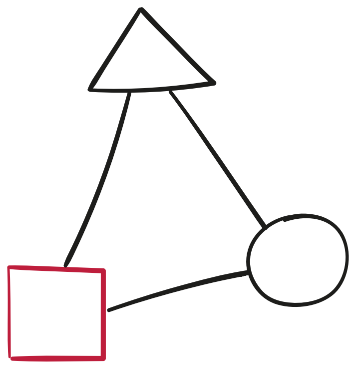
- Knowledge and theory of design goals
- Knowledge about products
- Knowledge about design processes

The main statement of this model of design research is that the phenomenon of designing can be considered from different perspectives. In consequence, the development of new design supports shall include these fields, or at least, clearly delineate the covered scope. Thus, throughout the following chapters, the five fields of design research will, at the one hand, ensure the comprehensiveness of the analysis of existing methodical approaches and, at the other hand, support the comprehensiveness of the elaborated new framework for product architecture design. In this way, the structure of this theses is constituted by the eight chapters as illustrated in Fig. 1.3.

Whereas this chapter comprised the main results of the *Research Clarification*, the subsequent two chapters will contribute towards *Descriptive Study I*. Therefore, in Chap. 2 a review of literature will be conducted in order to elaborate the theoretical basis of fundamentals of designing and current research on product architecture design. Based on this, design practice will be observed with regard to the identification of problems in designing the product architecture in order to answer RQ-1 in Chap. 3. In this way, the focus of the prescriptive part of this thesis will be narrowed down to the formulation of five sub-questions to RQ-2 (according to the five fields of design research), to be answered in the following chapters.

Therefore, the subsequent three chapters comprise the elaboration of a new support in *Prescriptive Study I* in three steps. First, in Chap. 4 five hypothesis will be formulated in order to provide initial answers to the five sub-questions formulated before. In a second step, these five hypotheses will serve as a basis for an extensive literature review in Chap. 5 aiming at the structured derivation of knowledge comprised within existing methods for product architecture design. This knowledge will be structured within a new framework for product architecture design in Chap. 6 that is based on three constituents in that the strains of the five fields of design research are brought together.

The application of the framework will be described in Chap. 7 to answer RQ-3 within *Descriptive Study II*. Therefore, insights from practice will be analyzed within two examples from industry in order to gain an initial validation of the support. Finally, in Chap. 8 the contribution of this thesis to both design practice and design research will be concluded based on a summary before a reflection of the limitation will serve for the derivation of future work in an outlook.



2

Theoretical basis

Product architecture in designing

The term *product architecture* is widely used in literature on engineering design. Many methodical approaches, for instance, focusing on product variety, process organization, or lightweight design refer to the term. However, within these approaches, product architecture is considered from different specific perspectives. This results in inconsistent definitions of the term and a lack of comparability and combinability of the existing knowledge as this chapter will show. Therefore, this chapter will provide a general overview of the state of the art related to product architecture in order to reveal the different facets to be considered within this thesis. It will be organized according to the structure illustrated in Fig. 2.1.

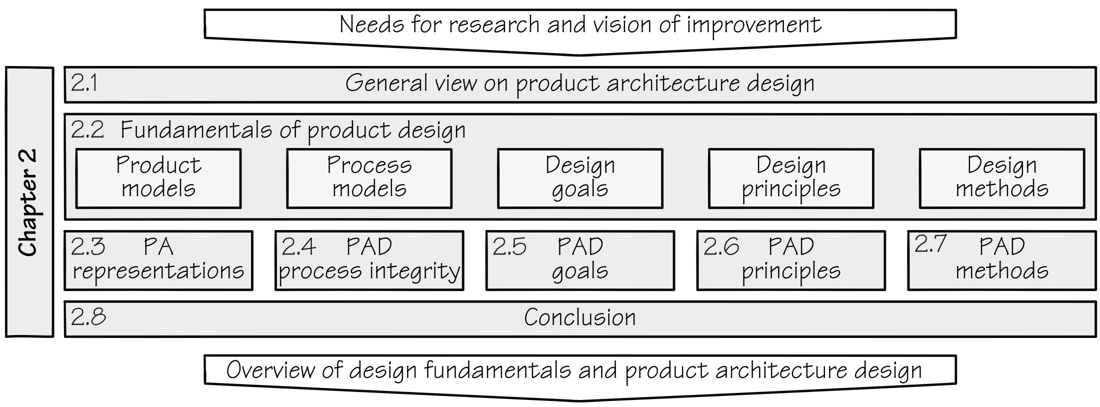


Figure 2.1: Structure of this chapter

In Sec. 2.1.3 general basics of design research will be described in order to outline the model of design research introduced in the preceding chapter and will provide the basis for the structure of this chapter. Thus, according to these five fields, in Sec. 2.2 a general overview of fundamentals of design will be elaborated. This general understanding is consolidated with regard to specific aspects of product architecture design in the following five sections: Sec. 2.3 and Sec. 2.4 will give an overview of descriptive models of representations of the product architecture and the process integrity of product architecture design. Sec. 2.5 will highlight implications of the topic by depicting goals for product architecture design. Based on that, Sec. 2.6 and Sec. 2.7 will describe prescriptive knowledge by introducing principles and methods. Finally, the chapter's findings will be concluded in Sec. 2.8.

On that account, the chapter's result is a structured overview of the fundamentals of designing and product architecture design. Its claim is not to give a complete picture of the state of the art. Rather, the focus lies on elaborating an understanding of the different facets of product architecture design within research. The model of design research provides the basis for this, and therefore, enables to place the state of the art upon basic theories of designing. Within the further progress of this thesis, especially in Chap. 4, it will become clear how this differentiated presentation of the state of the art allows traceability of the solution approach of this thesis.

2.1 General view on product architecture design

Product architecture design is related to various fields of design research. This section aims at providing an understanding of most relevant terms and demonstrates how the research conducted within this thesis considers general design theories as a basis for the systematization of specific knowledge related to product architecture design. Therefore, in Sec. 2.1.1 the context of product architecture design will be clarified by defining the term itself and setting it in relations to *designing* and *models* used in design. Based on this, examples of typical approaches supporting product architecture will be outlined in Sec. 2.1.2. This brief view on approaches motivates to take a closer look at theories on design research in Sec. 2.1.3 providing the fundamental structure for understanding approaches for product architecture design.

2.1.1 The context of product architecture design

In order to understand the phenomenon of product architecture design within the context of design research, at first, the term *designing* need to be defined. Therefore, designing can be considered as a process of transformation of an input into an output. Hubka and Eder specify the input and output as information in two conditions [HE96:4]: The initial condition describe "needs, demands, requirements and constraints (including the demanded functions)". The task of designing is to transform this information into a condition comprising the "description of a structure which is capable of fulfilling these demands". Therefore, the task of a designer is to provide a description of "what an artifact should be like" before it can be realized by the maker [Cro07:15f.].

In order to allow to describe the artifact to be designed appropriately to the activities of designing, within the European scientific community the terms *(required) properties* and *characteristics* got established. Weber defines these as follows [Web07:87]: Properties describe the (required) behavior of the product, and characteristics describe the structure, shape, dimensions, materials, surface etc. of the product. Integrating these terms in a definition of Dylla [Dyl91:18] designing shall be understood as all activities aiming at the determination of characteristics of a product in order to fulfill the required properties of the product.

During the process of designing, supporting means like *models* are used. These play a central role allowing designers to represent information in an appropriate way to perform the design activities. Only in this way, designers can be enabled to solve design tasks [Lin09:28] [Dör87:10]. The models serves in that case as the "language by which the designer [...] can elaborate, synthesize, evaluate, and communicate" [And94:103]. According to Stachowiak, models are abstract reproductions of reality that are closely linked to the specific purpose for that they are created [Sta73:73ff.]. The purpose is defined by the task to be supported by the use of the model. Whereas many models in science are created mainly to *analyze* a real object, models in design are used to *synthesize* the object at the same time [EWM+17:7] [EM17:77]. Taking these facets into account, the following definition of models will be used within this thesis: Models used in design are purpose-dependent abstract reproductions of real objects (e.g., the product to be designed, or the design process). Models allow designers to analyze and synthesize the modeled object.

Models used in design can serve a variety of purposes. The purpose defines which object is modeled. For instance, when the focus is laid on the product to be designed, models of the product – product models – are used, cf. Sec. 2.2.1. When facing tasks of handling the design process, models of the process – process models – are used, cf. Sec. 2.2.2. Therefore, methodical approaches used in designing can be based on product models and/or process models.

A specific class of methodical approaches include product models that are referred to as *product architecture*. Product architecture can be understood as a description of the *structure* or *arrangement* of elements of a product, cf. [AHM96:17] [Ulr95:420]. This definition will be specified in detail in Sec. 2.3.1. Depending on the purpose of representing product architecture, different specific product models can be used.

For instance, models that describe the interfaces between components to analyze and synthesize the effort to exchange components for configuring product variants, e.g. [Cae91:48f.]. Similarly, various other representations of the product architecture are proposed in literature, each representing different kinds of elements of a product (components, functions, working bodies, etc.), e.g. [Deu15:63], and relations (interfaces, dependencies, commonalities, etc.), e.g. [Ulr95:420]. Within the process of designing, these models are used in order to support specific activities that are referred to as *product architecture design*, that shall be defined in this thesis as:

> **Definition: Product architecture design**
> Product architecture design (PAD) comprises all activities aiming at the determination of the architecture of a product, e.g., of how elements of a product are arranged. In this way, product architecture design contributes to the fulfillment of a wide range of product properties that are affected by product architecture.

Along with the variety of representations of the product architecture, various different supports for product architecture design exist. Each of these supports focuses on a specific purpose defined by the product properties to be considered. This thesis aims at providing clarification of these different kinds of supports. One example will be described in the following subsection in order to demonstrate the versatility of approaches, and to highlight the resulting difficulty in comparing different approaches.

2.1.2 Versatility of approaches for product architecture design

Methodical supports for product architecture design – in the following *approaches for product architecture design* (PAD approaches) – are created for different purposes. It is not *one* PAD approach existing, but many specific approaches, each of which comprises a specific product model that represents aspects of product architecture. In the progress of this thesis, the variety of these approaches will be further outlined. At this point, a rough comparison of three approaches shall highlight their versatility, i.e., the differences of the aspects included in single approaches. The key ideas of the three approaches are illustrated in Fig. 2.2.

The first example (see figure left) shows the key idea of approaches for **modularization**. Erixon describes with *Modular Function Deployment* (MFD) such an approach aiming at defining modules, i.e., "building blocks with specified interfaces, driven by company-specific reasons" [Eri98:58ff.]. Therefore, the initial description of a product is analyzed regarding so-called *module drivers* like *recycling* or *technological evolution*. Each module

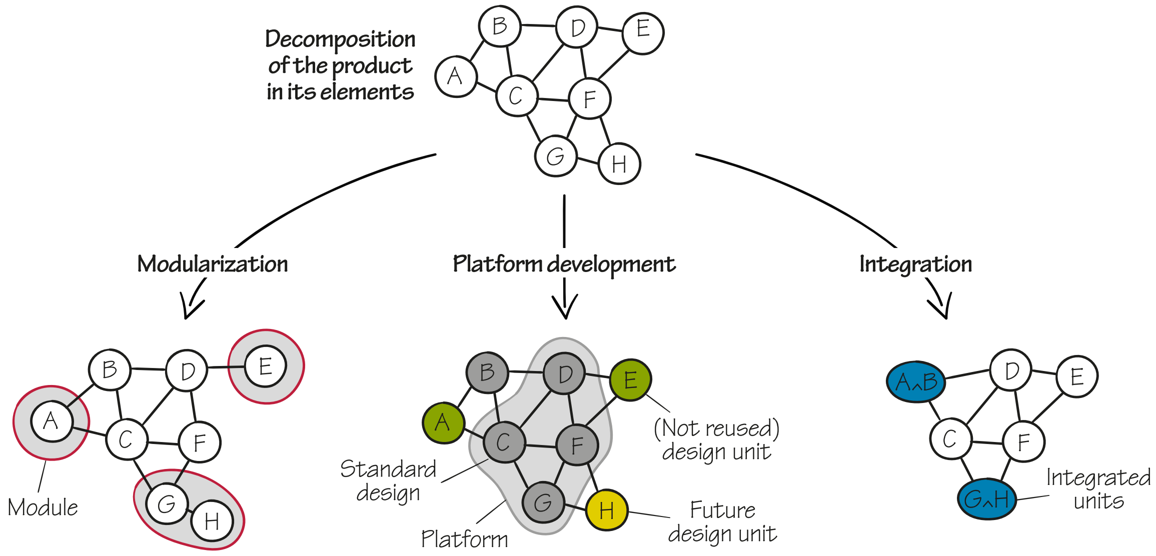


Figure 2.2: Illustration of the key ideas of three examples of PAD approaches on modularization, platform development, and integration

driver represents one specific reason for assigning an element of the product to a module that shall be designed in a way that it can be separated from the remaining product in specific life phases.

The second example describes an approach for **platform development** (see figure middle). For this, Harlou proposes to generate representations of the *Family Architecture* [Har06:81ff.]. By this, not only one product is considered, but the assortment of products within the company. On that basis, the descriptions of product variants are compared in order to identify commonalities. Elements can be described as *standard designs* that are reused in different variants, *design units* that are designed for only single variants, and *future design units* that are planned to be added in future product variants. Furthermore, groups of standard designs can be clustered into *platforms* that are used in the same composition for various product variants within a product family.

As third example, an approach for **integration** shall be introduced (see figure right). Ehrlenspiel et al. describe a *Strategy of the "One-part Machine"* that aims at reducing the number of parts of a product [EKL+14:329f.]. The key idea of the approach is to imagine the the product as made of one part. Then, step by step, the part is separated in elements as far as these separations cannot be avoided, for instance, for requirements regarding manufacture. In this way, it is pursued to finally reduce the number of separations in order to reduce the number of elements, and therefore, costs.

Even though the description of the three approach is limited to the bare essentials, is can be seen that their application results in far different transformations of the initially described product, compare Fig. 2.2: Modularization results in the separation of clusters of elements; platform development labels the elements according to commonality within the product assortment; integration leads to the consolidation of elements. In this way, each approach addresses different design goals, for instance, enabling recyclability (modularization), increasing variety (platform design), or reducing manufacturing costs (integration).

For achieving these goals, each approach makes use of design knowledge in the form, for instance, of formalisms to represent the product as well as principles and methods to design the product. However, the knowledge of each approach is limited to the scope necessary for the specific purpose. The overarching challenge motivating this thesis is to understand these different scopes of single approaches. Only in this way, it will be possible to unfold the approaches in order to allow to extract and combine the knowledge integrated for individual design situations. For this reason, a closer look at the discipline of design science in necessary to understand which kinds of knowledge are used in approaches for product architecture design.

2.1.3 Theories on structuring design research

In design science, Chakrabarti and Blessing see a lack of a common understanding within the research community, due to a missing underlying theoretical basis [CB14:34f.]. This impedes the exchanges of gained knowledge and limits its value when shared in the community. For this reason, for instance, Hubka and Schregenberger propose a model to structure knowledge about designing [HS88:109ff.], which shall be used in this thesis to place the work on a established theoretical basis. For this, the model classifies types of knowledge on two dimensions that will be outlined in the following.

The first dimension differentiates between *descriptive* and *prescriptive* knowledge, cf. [Hor01:1] [Ble03:1]. According to examples of Blessing and Chakrabarti [BC09:5], descriptive knowledge formulates and validates models and theories about the phenomenon of design with all its facets (people, product, knowledge/methods/tools, organization, micro-economy and macro-economy). In contrast, prescriptive knowledge builds on these models and theories, in order to improve design practice, including education, and its outcomes.

Besides the distinction between the descriptive and the prescriptive character of design research, another distinction can be made based on the focused subject of the research. Thus, Pugh claims that design research has its roots in the genuine engineering research that is concerned with technology [Pug90:68ff.]. However, this viewpoint does not include many non-technical aspects of designing and needs to be supplemented by a technology-independent branch of design process research, which aims at understanding and developing methods to improve designing. Hubka and Eder describe these two sides as the *product knowledge* and the *process knowledge* [HE96:82].

Superimposing these two perspectives, design research can be divided into four quadrants, see Fig. 2.3. Following the idea of Hubka and Schregenberger within this model of design research, specific fields can be entitled [HS88:109ff.], see also [HE88:220] [HE96:79ff.]. They originally entitle four fields representing the four quadrants. Within this thesis, a fifth field is added representing the consideration of design goals as these will play a central role within the further work as following sections will show.

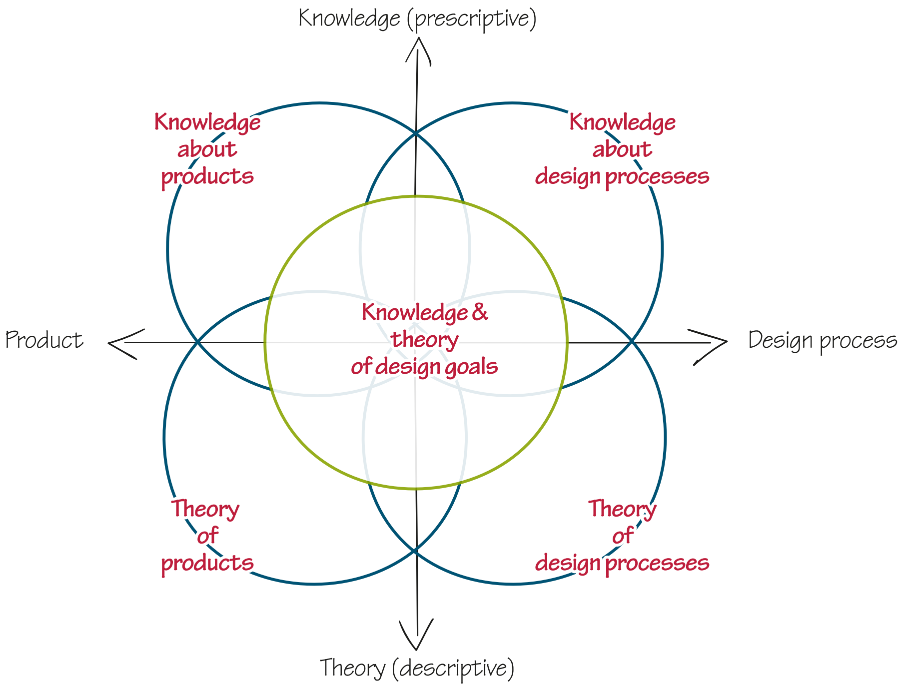


Figure 2.3: Fields of design research classified after Hubka and Eder, adapted and extended from [HS88:110] [HE96:82]

The design goals are allocated to the middle of the model as they can comprise knowledge of all kinds: Descriptive statements on the fulfillment of design goals within an existing product or process, and prescriptive statements on how a product or a process shall look like in order to fulfill design goals. Thus, the five fields of design research can be defined as shown in Tab. 2.1, whereas each definition is illustrated by an exemplary question to be answered within the field.

This model of design research will provide a basis for structuring the solution developed in the following chapters. The next subsection will outline contributions from state of the art related to the fields of design research in order to lay a foundation for the transfer of the fields to product architecture design.

Table 2.1: Fields of design research

Field of design research	Exemplary question
The **theory of products** describes, explains, establishes, and substantiates the product from all relevant viewpoints for designing [HE96:82].	How can the product be described in order to represent its characteristics in an appropriate way to evaluate effects on required product properties like its weight?
The **theory of design processes** describes, explains, establishes and substantiates design processes in their socio-technical context [HE96:82].	How can the design process be described to represent its activities in an appropriate way to evaluate effects on process properties like the process efficiency?
The **theory and knowledge about design goals** describes, explains, establishes, and substantiates design goals and provides knowledge about how to access product and process related knowledge to address these.	How can design goals be described in order to allow designers to recognize and prioritize design goals to address these within the appropriate definition of the design process and the product?
The **knowledge about products** provides ways and means (guidelines, design catalogs, principles, etc.) by which a product should be designed in order to realize the required functions and fulfill the required properties [HE96:82].	How can knowledge about products be provided to designers (e.g., in the form of principles) to support the definition of most suitable product concepts?
The **knowledge about design processes** provides operators of the design process (methods, tools, procedures, etc.) for successfully performing and managing design processes [HE96:82].	How can knowledge about design processes (e.g., in the form of methods) be provided to designers to support the definition of the most suitable design processes?

2.2 Fundamentals of product design

Product architecture design is a branch of design research closely connected to general design theories. A consideration isolated from this would prevent a comprehensive understanding of the phenomenon of product architecture design. Therefore, this sections aims at outlining central design theories to highlight those definitions of central terms derived from literature. Afterwards, in Sec. 2.3 to 2.7, the state of the art specific to product architecture design will be described on the basis of these fundamentals. The structure of this section is oriented at the five fields of design research, see Sec. 2.1.3. Accordingly, the subsections will focus on following terms:

- **product models** (within the *theory of products*), see Sec. 2.2.1
- **process models** (within the *theory of design processes*), see Sec. 2.2.2
- **design goals** (within the *theory and knowledge of design goals*), see Sec. 2.2.3
- **design principles** (within the *knowledge about products*), see Sec. 2.2.4
- **design methods** (within the *knowledge about design processes*), see Sec. 2.2.5

Within each subsection, first, the purpose of knowledge within the field will be highlighted, second, the constituents of the included knowledge will be outlined, and third, approaches will be depicted focusing on a knowledge provision.

2.2.1 Product models in design

Within a design process, the product has to be examined from a range of perspectives. For this, designers create representations of the product – *product models* – that provide them the necessary information for analysis and synthesis.

The purpose of product models

The goal of designing is to elaborate a description of a product to be manufactured, see Sec. 2.1.1. In the process towards the final description designers can make use of product models. Thereby, a defined subset of attributes of the product (under development) is represented in an adequate and operatively appropriate way [Fra76:36], for instance, by modeling its functions within a function structure, or its geometry within a CAD model. In this way, the product model allows the designer to purposively "communicate" about the product by focusing only on that information suitable for solving the problem under consideration [Buu90:34].[1]

The purposes of product models are discussed in literature from various perspectives, cf. [EWM+17:10] [AHC15:44] [DB12:3]. Besides general activities of a design process like product visualization, life cycle support, communication, or process management, two key purposes are highlighted according to the before defined two categories of problems: analysis problems and synthesis problems, see Sec. 2.1.1). Product models can support both types of problems, cf. [Web14:332] [EWM+17:10]:

- **Support of product analysis**: Product models allow designers to understand the product properties, for instance, by discovering the product's weight by modeling the products geometry.
- **Support of product synthesis**: Product models allow designers to determine product characteristics, for instance, by finding new concepts for the embodiment in order to reduce weight.

Therefore, the terms *properties* and *characteristics* play a central role in the definition of product models. In the following, these will be considered in more detail.

[1] In literature, definitions derivating from this definition exist: Accordingly, a *product model* represents the totality of all information about a product during designing, also called *integrated product model*, see [Koh14:54]. The definition within this theses clearly delineates from this viewpoint.

Constituents of product models

In order to fulfill the described purposes, product models have to include information about properties and characteristics. The differentiation of these two types of attributes illustrate Hubka and Eder with the example of designing a bridge [HE96:109]: Accordingly, when designers describe a "system of steel profiles, which could form a bridge" they use the product characteristics, but do not make any statement of the *value* of the designers' work. Therefore, designers must be able to unfold the product properties like the bridge's load capacity, reliable safety, lifetime as well as aesthetic appearance. Only the description of both the product characteristics and product properties allows to evaluate the physically appearing product plus its value.

Weber highlights this perspective on designing within his *Characteristics-Properties Modeling* (CPM) approach [Web07:86ff.]. Therein, designing is described as an interplay between analysis and synthesis, whereby analysis describes the activities to understand the product properties from the descriptions of its characteristics. Synthesis describes the determination of characteristics in order to fulfill required properties. The definitions of the terms characteristics and properties according to Weber [Web07:87] provide the basis for this (see also, [And94:104f.]):

- Product characteristics describe the appearance of a product, for instance, its structure, shape, dimensions, materials, and surfaces. They can be directly influenced or determined by the designer.
- Product properties describe the product's behavior, for instance, weight, safety, reliability, aesthetic properties, manufacturability, testability, environmental friendliness, and cost. They can *not* be directly influenced by the designer.

Accordingly, a product model used by designers to support activities of analysis and synthesis requires to include both, the characteristics as well as the resulting properties. Therefore, a product model shall allow to understand the *relations* between these [Web12:49f.]. For instance, a function structure includes the description of product functions and its interactions as product characteristics (since the designers can influence these directly). From this, designers can draw conclusions on properties like functional safety (when redundant functions are designated), or the overall product functionality provided for the product user.[2] Similarly, a CAD model includes the description of the product's geometry as its characteristics. It allows designers to evaluate properties

[2]Within this thesis "functions" are defined as characteristics in contradiction to the definition of Weber [Web07]. However, from the author's point of view, a distinction has to be made between the functions as intended to be included in a product and the function properties. These viewpoint is supported, for instance, by Howard and Andreasen [HA13:235f.] and Birkhofer [Bir80:21].

like weight, required space, or manufacturability. Therefore, based on the outlined literature, product models will be defined as follows within this thesis:

> **Definition: Product models**
> Product models are representations of the product (to be designed) comprising all information required within specific design situations to evaluate relations between product characteristics and product properties. In this way they allow designers to analyze the product properties to synthesize the product characteristics.

Depending on the properties to be evaluated (analysis problem) and/or the characteristics to be defined (synthesis problem) different product models can be applied. In literature, numerous approaches exist aiming at guiding the purposive application of specific types of product models. Generic approaches provide, for instance, Rude [Rud98:255ff.], Suh:191ff. [Suh98], Roth [Rot00:32ff.], and Pahl et al. [PBF+07:128ff.]. A clear illustration of product models with the description of the included characteristics and properties of each model is given by Birkhofer [Bir80:20ff.].

Classification of product models

Within a design process, different product models are applied depending on the given design task. The classification of the product models can be made by the type of characteristics to be defined or by the properties to be evaluated. Thus, many theories define design as process of concretization of the product characteristics and properties. Accordingly, for instance, Roth describes product design as progressing from product model to product model by increasing concretization of these models [Rot00:44f.], first described in [RFS71:337f.]. According to this understanding, during a design process various design states occur for that product models are generated including "all the information about a design as it evolves" [EGB11:346]. Based on these approaches, during a design process, a "chain of product models" of increasing concretization is passed through that built on each other [Fra76:36] [Bir80:26].

Accordingly, several authors define product models in allocation to levels defined by the degree of concretization of the included characteristics. For instance, Ehrlenspiel and Meerkamm describe a pyramid of product models including the levels of *requirements, functional solutions, principal physical solutions, embodiment and material solutions*, and *production and assembly solutions* [EM13:39]. Other approaches focus on the properties to be analyzed with a product model like manufacturability, cost, weight, etc. [Vaj01:1]. Thus, product models can also be classified according to the properties, which allows designers to select appropriate models for specific design situations [AKP+06:7f.].

2.2.2 Process models in design

While product models represent the product under development, *process models* represent the design process that is defined to structure the designing activities. Depending on the objective of examining a process, different process models can be defined.

The purpose of process models

Designing products can be described by a process of information transformation, see Sec. 2.1.1. In most cases, a design process is divided into several stages (also called phases) including activities performed by different designers. To describe those processes, *process models* can be generated representing that information required by the user of the model. Depending on the users' intention, different representations can be used, each describing the design process from different perspectives [OEC+05:62].

The purpose of the process models' use can vary widely. Therefore, Browning and Ramasesh provide a purpose-based framework for the classification of process models including four categories of purposes [BR07:219]: design process visualization, design process planning, design project execution and control, and design project development. Against the background of the categories of problems described in Sec. 2.2.1 and the assumption that product models and process models generally fulfill similar purposes, these purposes can be conflated to two main purposes [EWM+17:9]:

- **Support of process analysis**: Process models allow designers to understand the process properties, for instance, by evaluating the communication effort in distributed development projects.
- **Support of process synthesis**: Process models allow designers to determine process characteristics, for instance, by defining at which stage of a development project which product models shall be generated.

Similarly to the definition of product models, process models need to include defined constituents here mentioned as process characteristics and process properties. These are explained in the following.

Constituents of process models

In contrast to the extensive literature available describing theories about product models, no consistent theories on design processes are established within the domain of design research. Nonetheless, various authors describe different types of process models and highlight criteria for their differentiation, e.g., [HE96:125f.] [OEC+05:1f.] [GB12:171f.] [WC17:4f.]. Based on this, reoccurring constituents of process models can be differentiated referring to product properties and characteristics according to the CPM approach of WEBER, see Sec. 2.2.1. Therefore, process characteristics, as well as process properties, can be defined as the main constituents of process models.[3] A categorization and allocation of examples provide HUBKA and EDER as follows [HE96:152]:

- **Process characteristics** describe the structure of a design process including, for instance, the activities carried out, the processed information (product models), the involved designers, and the methods and tools applied. Process activities can directly be influenced or determined by the designers.
- **Process properties** describe the process' behavior, for instance, the quality of the output (the product description), the design duration, the efficiency and effectiveness, and the risk for the designers. Process properties can *not* be directly influenced by the designers.

Therefore, the following definition for process models is derived from literature for this thesis:

> **Definition: Process models**
> Process models are representations of the design process (under definition) comprising all information required within specific design situations to evaluate relations between process characteristics and process properties. In this way, they allow designers to analyze the process properties and synthesize the process characteristics.

The constituents of process models shall be illustrated on the example of a process representation after GERICKE et al. [GBG+10:11], see Fig. 2.4. The chart shows a formalism to describe design process by stages (columns) and the design states considered within the activities within a stage (rows). Thereby, the design states correspond to specific product models that describe, for instance, the need, the problem, the requirements, the function structure etc. The figure illustrates as an example of applying this formalism to the generic design approach after PAHL et al. [PBF+07:130].

Within this process representations, process characteristics are illustrated in a way that it allows to evaluate the process properties. Thereby, the main focus lies in the evaluation of the property describing the quality of the design process in terms of ensuring the development of products fulfilling the demanded requirements. Following the

[3] However, literature does not agree on the terms as defined within this thesis. For instance, ECKERT and CLARKSON describe *process characteristics* as the behavior of the process [EC05:14] clearly contradicting other definitions. HUBKA and EDER uses the terms *aims* (according to properties) and *operators* (according to characteristics) [HE96:152].

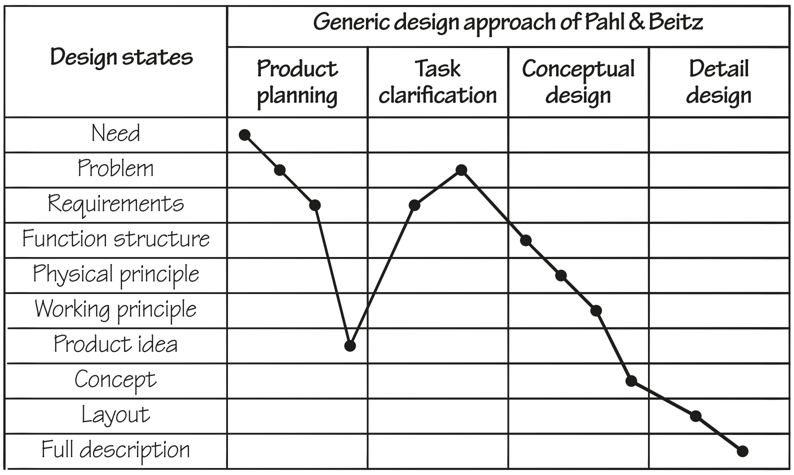


Figure 2.4: Exemplary formalism to represent a process by stages and the considered design states (product models), adapted from [GBG+10:11] [GM11:5]

approach of Pahl et al., this can be achieved by progressing subsequently from product model to product model.

Classification of process models

A classification of process models according to process characteristics focuses on the determined elements of the process as the stages, the processed information, the involved stakeholders etc. For instance, the before described general design approach of Pahl et al. lays the focus on the stages passed within the course of designing [PBF+07:130]. Other approaches from Systems Engineering focus rather on the product models analyzed and synthesized within the process, cf. [MAM+17:141]. Process models from economics, for instance, swim lane models focus on the participants of the product and their interactions, cf. [ISO13].

A classification of process models according to the question of the relevant process properties to be evaluated can be made, for instance, regarding the target group working with the process model. A designer, for instance, requires a detailed description of single activities to be performed by himself. A manager requires a top-level representation of the whole design projects with a focus on Key Performance Indicators (KPIs). Therefore Wynn and Clarkson define categories for process models (micro, meso, and macro) each of them allowing to evaluate the process from a different perspective [WC17:5].

2.2.3 Design goals

A central challenge within a design process is to anticipate the behavior of a product and formulate a desired behavior by required properties. Those required properties will guide the design process as they serve as *design goals* against which the designers evaluate their activities.

The purpose of specifying design goals

In the preceding subsections, a design problem was described from the perspective of the product as well as the design process. For both perspectives, it has been found that the required product properties are central elements within the problem definition (the product must fulfill the required properties, and the design process must allow to achieve the required properties). Thus, essential to the problem definition is the specification of a goal describing an image of a future situation, which is preferred to the present one [Roo02:90]. Even though the goals may change within a design process, it is important to define goals clearly to be able to determine whether elaborated solutions to the problems are appropriate or not [Cro08:191f.].

However, the definition of goals is carried out at various levels of a company including different stakeholders. This results in the definition of different types of goals [Ebe15:56]. Therefore, on a top-level within a company, goals are traditionally defined based on success factors as *cost*, *quality*, and *time* – nowadays often supplemented by *product variety*, *service*, and *flexibility* [Kal05:5]. Design goals are derived from those strategic goals [Eil99:61]. In parallel, goals for other domains than design like marketing, production, finances, and project management are defined. Therefore, design goals are manifoldly interacting with other goals within other domains and levels of the company [Bad07:19f.].

Within the design process, design goals define the way in which activities of analysis and synthesis are performed. The *ZHO Model* after Meboldt [Meb08:156ff.] illustrates this, cf. [Rop75:32f.] [NFI97:266ff.]. Thus, the *ZHO Model* describes product design as an interplay of three systems: The system of goals (*Zielsystem*), the system of activities (*Handlungssystem*), and the system of objects (*Objektsystem*). Any design activity (within the system of activities) aims at manipulating the transitions between the system of goals and the system of objects by analysis (understanding the impacts of the object on goals) and synthesis (determining objects in order to fulfill goals). Therefore, design goals are drivers for any design activity and are a central element to be clarified and modeled within a design process.

Describing design goals

Resulting from the importance of design goals, several approaches provide support for the definition of design goals and its integration into further activities of the design process. For instance, the design approach of Pahl et al. [PBF+07:130] includes the elaboration of a requirements list that specifies the design goals for the development at the first stage. In further stages, the evaluation against and the updating of requirements is defined as a continuous activity. Similarly, other approaches like the *Munich Product Concretization Model* consider requirements as overarching elements for evaluating product models of different concretization [PL11b:28].

Weber provides an illustrative formalism for integrating design goals into the use of product models [Web07:86]. Within his CPM approach, see Sec. 2.2.1, he considers design goals as required properties. These required product properties serve for a continuous evaluation of actual properties as apparent in applied product models (including characteristics and properties). Thus, the consideration of required properties within a design process allows an iterative implementation of activities of analysis, synthesis, and evaluation.Therefore, the CPM approach describes required properties similarly to the ZHO model as an accompanying element to design activities. Weber specifies design goals thereby by considering a desired state of product properties as design goals. The following definition of design goals can be derived from this:

> **Definition: Design goals**
> Design goals anticipate a future state of the product that is preferred to the current one by describing its required product properties. In this way, design goals guide designers through activities of analysis and synthesis of solutions for the design task.

Generally, design goals are used in designing to define appropriate product models (allowing to analyze those product properties described by the design goals) and process models (allowing to analyze those process properties describing whether the design goals are addressed by the process).

Classification of design goals

In literature, different approaches exist that provide schemes for classification of design goals each addressing a perspective suitable for a specific design situation. Many of those approaches focuses on a differentiation of technical aspects of a product. Thus, for instance, Patzak provides an approach differentiating *"wirk" properties (functionality), condition properties (physical appearance)*, and the *behavior properties (product's behavior in use)* [Pat82:33ff.]. Andreasen et al., similarly, names *function properties* and *relational properties* (the product behavior in use), and adds a category of *allocated properties* referring to symbolic or devotional properties [AHC15:316]. In this way, these types of classification schemes focus on the value of the product offered to the customer.

Other approaches highlight strategic aspects of the company. For instance, within the domain of design research approaches considering the product life cycle are becoming more and more established, cf. [Bir11:348ff.]. In this way, the focus is shifted from the use phase of the product to other stages like the development, production, or recycling of the product. From the field of economics research, several approaches describe business models setting the product more directly in context of the company's success. For instance, Osterwalder provides the *Business Model Canvas* supporting the definition of a company's strategy [Ost04:42ff.] [OP10:18ff.], see Fig. 2.5. In the center of the model, *product innovation* describes the value proposition provided by the product. On the left side, three fields contribute towards the *infrastructure management* aiming at an efficient creation of value. On the right side, the *customer interface* includes all areas of the company interacting with the customer.

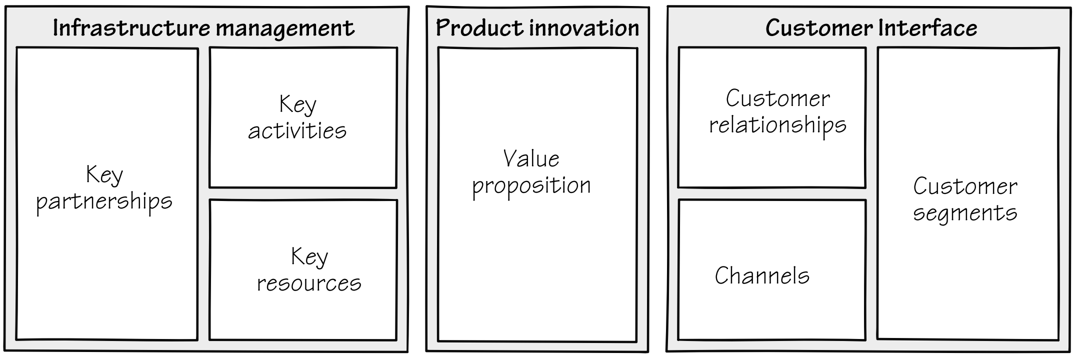


Figure 2.5: Classification scheme for company goals (including design goals) within the *Business Model Canvas* after Osterwalder, adapted from [OP10:62]

2.2.4 Design principles

While product models are *descriptive* representations of products, *design principles* provide a *prescriptive* counterpart including sound knowledge for supporting product analysis and synthesis.

Purpose of design principles

Besides the creativity of the designers, the *knowledge* available for them plays a key role in designing [Ink16:77]. The knowledge involves all abilities, skills, and expertise of designers for solving problems [PRR12:23], see Sec. 2.1.1. Hatchuel and Weil [HW03:5ff.] illustrate this in their *C-K Theory* by explaining that new concepts (e.g., new ideas in a design process) always arise on the basis of existing knowledge.

In a similar way, other authors argue that design knowledge is necessary for successful designing. For instance, Ziebart describes the design process as the evolution of various product models, for instance, due to concretization. Each step in between is made by integrating existing design knowledge what is called *knowledge engineering* [Zie12:49]. Based on the same assumption, several approaches aim at the provision of knowledge in the form of information collections. In those approaches, the provided knowledge is refereed to, for instance, as *design guidelines* [Bis10:84], *elementary solutions* [Rot01:1], *design prototypes* [Ger90:29], *design patterns* [WH16:103], or *design principles* [FYW15:1].

In essence, all these terms are meant in the same way providing "general rules for the design activity, which will frequently favor good solutions" [Buu90:34]. In the following, the term *design principle* will be used in this meaning to provide existing knowledge elements to designers supporting analysis and synthesis.

Describing design principles

The first step for the provision of design knowledge is the formalization of the knowledge, for instance, by extracting knowledge from proved products or directly from the designers' experience. Therefore, a "code" needs to be defined in order to allow modeling the knowledge in a form appropriate to be used within design processes [Nor11:49ff.]. According to Andreasen [And94:106f.] several different aspects of the modeled objects need to be considered, for instance, the language and symbols used for modeling, the degree of abstraction (e.g., functional or physical description), and the degree of detail (e.g., assembly or part). Furthermore, analogous to the definition of product models, it must be described clearly which characteristics of the modeled objects are included in the principle's description as well as which properties are affected by the principle's application, cf. [Now97:41,62]. Only in this way, a design principle can fulfill its purpose to support designing.

According to these premises, Weber and Husung [WH16:103f.] propose to describe design principles (*design patterns* according to their definition) within the CPM approach, see Sec. 2.2.1, by characteristics and properties, and the known relations between these. Therefore, a design principle can be considered as a defined section of a product model that is regarded as the knowledge that can be applied within another context. In this way, the defined knowledge on relations between characteristics and properties is formalized appropriately for the use within other contexts. Then, within other design situations, designers can identify the design principle when needed and apply it by inserting the knowledge into a product model as a "puzzle part". Therefore, design principles always require to include the description of characteristics *and* properties in order to allow drawing conclusions on the appropriateness of specific design decisions. This provides the following definition of the term:

> **Definition: Design principles**
> Design principles are expedient representations of product-related knowledge containing statements on how specific arrangements of product characteristics implicate product properties. In this way, design principles can enhance designers to apply already gained knowledge to new design problems.

With this definition, it becomes clear that a design principle follows the same codification as a product model. However, while a product model is generated to describe and develop a solution for a given problem, a design principle is explicitly extracted from known solutions. In this way, design principles serve as catalysators applied in different contexts [Koh14:50], or: to be placed (as a "puzzle part") into the incomplete product model used for generating a solution for a problem to "complete a relationship that is incomplete in the problem statement" [Faw87:83]. Thus, a central challenge for the formalization of design principles is to identify a suitable scope of the product description (include appropriate characteristics and properties) anticipating the need of future designers to include this excerpt of knowledge for providing design principles.

Provision of design principles

For providing design principles, various approaches exist in literature, often related to a specific goal (e.g., DfX approaches), or specific types of products (e.g., mechatronic products). Besides the formal description of the design principles, a central element of these approaches is a "recall scheme to provide access" to the design principles, i.e., a support for the identification of design principles that can be applied within a specific design context [Now97:42]. Gaag calls this element *access logic*. It is arranged between the designer requiring knowledge within a design situation and the information storage containing the codified knowledge of which only a small part may be suitable for the request of the designer [Gaa10:34]. Fig. 2.6 illustrates these relations.

The criteria of the access logic need to allow designers to identify suitable knowledge elements to be appropriate to both the designers' description of the problem situations and the information included in the description of the knowledge elements. In this way, a clear conjunction of the problem and possible solutions can be indicated. According to the approach to describe design problems on the basis of product models, see Sec. 2.2.1, design principles can be identified on the basis of characteristics and

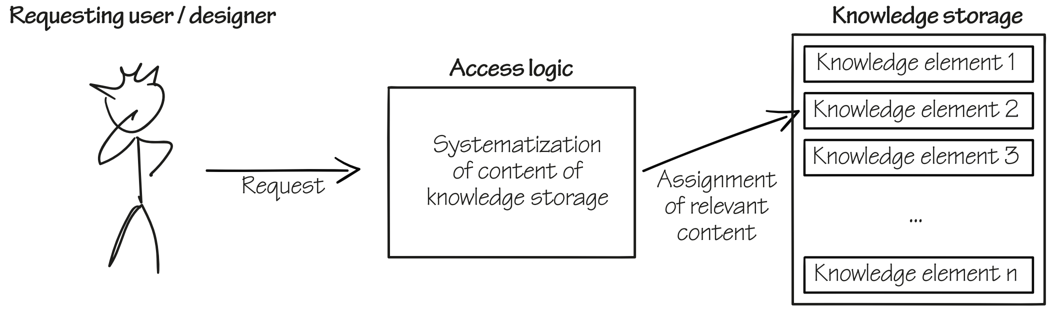


Figure 2.6: Aquisition of formalized design knowledge supported by an access logic, adapted from [Gaa10:34] [Ink16:89]

properties. Existing approaches in literature include this systematization within the access logic whereas the focus is often rather on characteristics *or* properties.

As a first of two examples, the *Design Catalogs* (German: *Konstruktionskataloge*) after Roth shall be described, cf. [RFS71, Rot01, Rot82]. These are defined as knowledge storages "suited to methodical designing regarding their access possibilities and structure" [Rot01:1ff.]. Product knowledge ("object catalogs" and "solution catalogs") is structured regarding the characteristics of the knowledge elements, for instance, functions, physical effects, or geometrical features (within the *Gliederungsteil*). For each knowledge element an arrangement of functions, specific physical effects, or geometry proposals, assumptions on the resulting properties are included (within the *Zugriffsteil*) in order to allow designers to choose those elements most suitable for their design task.

In contrast to Roth, Altshuller provides principles that are accessed on the basis of product properties, cf. [Alt02, Alt99]. Therefore, he derived a list of 40 principles for solving technical contradictions from existing solutions [Alt99:138ff.]. These principles are accessed based on a *Contradiction Matrix* in that various product properties are being opposed that can stand within a goal conflict, i.e., no solutions are known to fulfill both properties. Principle shall indicate solutions on how to arrange product characteristics in order to fulfill the contradicting properties.Similarly, various other approaches for principles' provision exist in literature. Even though not always explicitly mentioned, their description and structuring of principles is based on product characteristics and properties in most cases.

2.2.5 Design methods

Analogous to the relation defined between design principles and product models, *design methods* provide prescriptive knowledge elements to be implemented into design processes respectively the process models.

Purpose of design methods

Sec. 2.1.1 and 2.2.2 characterized the process of designing as problem-solving, i.e., overcoming obstacles during the process of elaborating a suitable product description. Design methods can support problem-solving by describing a recommended sequence of activities providing guidance for designers [Buu90:35]. In this way, designers are enabled to execute appropriate steps of transforming descriptions of the product until the final description is achieved [HE96:130]. However, thereby the methods only can provide an operative guidance, but do not substitute the designers' creativity. Andreasen et al. highlight this by describing methods as stepping stones on the path of designers, whereas the designer can only bridge the small gaps between the stepping stones "via their understanding, mindset, and creativity" [AHC15:6], see Fig. 2.7.

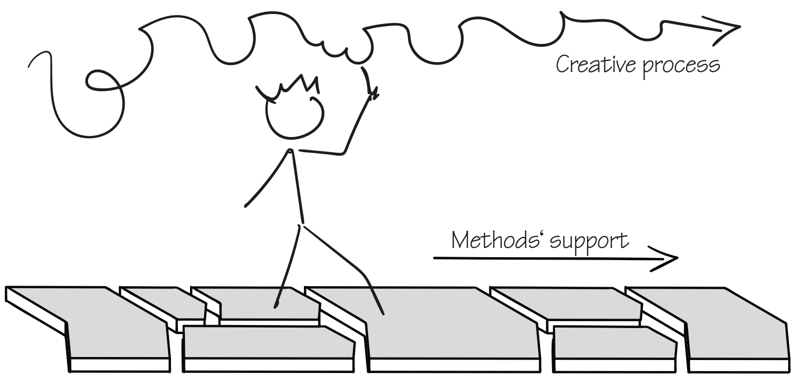


Figure 2.7: Progressing within the design process by "stepping" from method to method bridged by the designer's creative mind, adapted from [AHC15:6]

In order to provide this support, Newell names four key features methods have to incorporate [New83:202ff.]:

- the description of a specific way to proceed providing guidance for the designer (the "stepping stones"),
- a rationale for increasing the chance of solving a problem,
- a general applicability to various problems, and
- an observable execution in order to allow to ascertain the methods' application.

The first two features describe the main purpose of a method to support designers in identifying appropriate procedures for a specific design problem. However, thereby, the methods cannot ensure the success of their applications. Roozenburg and Eekels highlight this limitation of methods as rather being of a heuristic nature, and not algorithmic since "they aid in finding something, but there is no guarantee that it will be found and by everyone" [RE95:42]. The third and fourth feature describe methods as formalizable knowledge analogous to the *C-K Theory*, see Sec. 2.2.4. Thus, according to

Eckert and Clarkson, a method is not just any procedure within a design process, "but something that is recognized as a recurring event and hence has a meaning beyond the single instance" [EC05:20]. This is a necessary prerequisite for the identification of expedient procedures and for a suitable description of the methods, to be applied in different contexts.

Describing design methods

The way a method is described depends on the specific method's purpose and the context of application. These factors define which constituents shall be included in a method's description, for instance, the description of activities to be carried out, the affected design goals, the roles and competencies of method users, the allocation to a design process, etc. Several authors provide meta models for describing design methods each putting the focus on different aspects within the description, cf. [ARB+14, Bav18, BKB+02].

At this point, the variety of possible constituents of method's descriptions shall not be considered in detail. Rather, it shall be focused on those relevant for a consistency to the before defined constituents of process models, see Sec. 2.2.2. These necessity arises when design methods are understood as "puzzle parts" to be included into design processes – analogous to the description of design principles as puzzle parts within product models, see Sec. 2.2.4. Thus, a design method is regarded as an extract of a (successful) design process that is formalized as a knowledge element to be implemented in other design processes. Based on this assumption, a design method needs to include a description of the process characteristics (e.g., the activities to be performed) as well as the process properties (e.g., the design goals in the form of addressed product properties). Literature provides several schemes for method's descriptions including these two constituents whereas often the focus lies rather on one of these as following examples show.

Process characteristics are described within methods, for instance, by depicting activities to be carried out as well as their interplay. Therefore, well known methods like *Quality Function Deployment (QFD)*, *Failure Mode and Effects Analysis (FMEA)*, or *Method 6-3-5* include such activities within procedures with a specific purpose. Other methods are described against the background of a more general applicability. For instance, the *Plan-Do-Check-Act (PDCA) Cycle* [Dem00:131f.], the *Munich Procedural Model* [Lin09:46ff.], or the *Systems Engineering Problem-Solving Approach* [DH99:96] describe basic activities that can be applied in different use cases. The last-mentioned approach of Daenzer and Huber, is shown in Fig. 2.8. The approach is constituted by six basic activities that can be applied in various orders within different contexts of problem solving.

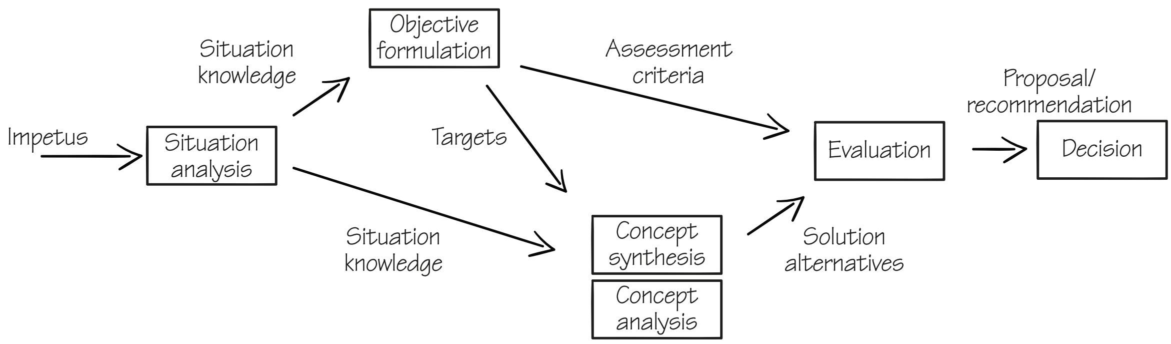


Figure 2.8: Systems Engineering Problem-Solving Approach by Daenzer and Huber, adapted from [DH99:96]

Process properties are highlighted in methods' descriptions when the focus lies on the specific purpose of the methods application. Whereas the general problem-solving approaches shown before can be applied in various contexts, other methods are defined in many cases for achieving specific goals as process properties that are referred to as *DfX methods*.

Against the background of these two perspectives on design methods, they can be defined with a clear analogy of the definition of design principles, see Sec. 2.2.4.

Definition: Design methods
Design methods are expedient representations of process-related knowledge containing statements on how specific arrangements of process characteristics (e.g., through providing recommended sequences of activities) implicate process properties (e.g., through providing rationales on how design goals can be achieved). In this way, design methods can guide designers through the process of solving specific problems based on approved process knowledge.

Therefore, in contrast to process models that aim at the *understanding* of design processes, design methods are sequenced sections formulated in a *prescriptive* way. Therefore, a method shall enable designers to carry out specific activities, while process models only allow them to describe the process in an appropriate way to understand its properties. However, often process models are the basis for identifying necessities for implementing design methods. Therefore, many approaches in literature focus on the provision of design methods that shall allow designers to identify methods most suitable for specific design situations.

Provision of design methods

In order to better understand the design methods' use in industrial practice, several authors have investigated on the actual implementation of existing design methods. They recognize that in many cases the level of implementation is very low despite the fact that methods fitting to the given situations are existing in literature, cf. [Bav18:2] [LB11:12ff.] [Ara01:16f.]. The reasons for this are various. Andreasen et al. highlight that in many cases a gap exists between the method creator's interpretation of the use situation and the actual situation in industry use [AHC15:54]. They resume that designers must be allowed for *mastering methods*: "Part of good practice is to master methods, being able to understand them, and adapt them to the specific project" [AHC15:80]. For achieving this, a central approach is the provision of method descriptions in a way that designers can access those information to be able to evaluate and apply them in specific design situation, also referred to as "situative" method provision [Pon07:121ff.].

In literature, several approaches for method provision exist that are structured regarding the process characteristics and/or properties. For instance, Zier et al. [ZBB12:1215] lay the focus on the process characteristics and structure the methods' proposed steps according to so-called "elementary methods" representing overarching activities reoccurring in design processes. Lindemann [Lin09:247ff.] concentrates on the method goals' by providing the process characteristic of fulfilling product properties. An example for an approach combining both perspectives is the web-based method portal *Methodos* that structures methods according to their procedure and main goal [Bav18:131ff.,173ff.].

2.3 Representations of the product architecture

The term *product architecture* is widely used in the context of designing both in industrial practice as well as in academia. However, its definitions in literature are manifold and in many cases not consistent. Therefore, different *representations of the product architecture* (PA representations) exist. Based on the definition of product models (see Sec. 2.2.1), this section will give an overview of understandings of the term in Sec. 2.3.1. This understanding will be illustrated by examples of representations of the product architecture in Sec. 2.3.2. Finally, the actual integration of those representations into design processes will be highlighted in Sec. 2.3.3.

2.3.1 Scope of representations of the product architecture

Definitions of the product architecture are various and can be found in publications of several branches of design research. Depending on the specific context, different *dimensions of PA representation* are highlighted what obscures a clear definition of the term. Within this section, three dimensions of PA representation will be exposed that are recurrently highlighted in literature. These dimensions describe classes of product characteristics included in the corresponding product models. An overview of the three different viewpoints is illustrated in Fig. 2.9 whereas each will be described in the following based on an analysis of existing definitions of the product architecture, see Appendix A.

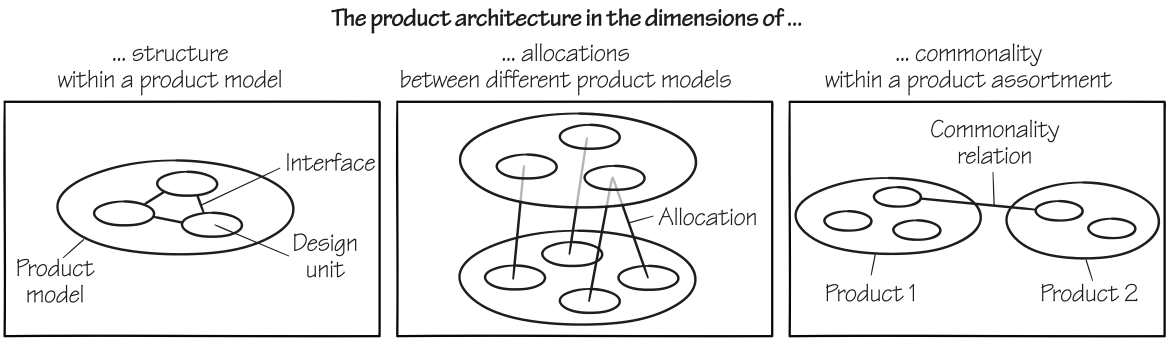


Figure 2.9: Dimensions of PA representation

1) Product architecture as the *structure* of a product

The first dimension of product architecture highlights its capability to describe the *structure* of a product. However, especially in American literature the terms *architecture* and *structure* are often used synonymously what complicates a differentiation of the terms [AMH04:13]. Therefore, Fixson describes product architecture as "a comprehensive description of a bundle of product characteristics, including number and type of components, and number and type of interfaces between those components" and follows that it is the "fundamental structure of the product" [Fix05:346f.]. Similarly, Wie defines the core of the product architecture as describing a "set of items and how they are arranged" [Wie02:6]. Crawley et al. specify the product architecture as "an abstract description of the entities of a system and the relationships between those entities" [CWE+04:2].

These definitions have in common that the product architecture represents elements of the product (components, items, entities) as well as their relations (interfaces, arrangement, relationships). These authors do not further specify the elements of the product or their relations. Instead, Wie argues that several different elements of a product can be included without any prescribed "formal vocabulary and grammar" [Wie02:6]. Andreasen et al. highlight this fact by describing product architecture as the "structure of a product [...] seen from an expedient angle" whereas the angle can be defined, for instance, by the product properties or the life phases considered

[AHM96:17]. Similarly, Erens argues that, depending on the purpose, the elements of a product architecture can be described by product functions, technology, or physical components [Ere96:25ff.].

2) Product architecture as *allocations* between different product models

The definitions above focused on the structure of the product of elements of the same kind. Other definitions describe *allocations* of elements of different kinds, i.e., of different product models, see Sec. 2.2.1. Thereby, in most cases, allocations between the functional and the physical description of the product are highlighted. Thus, Eppinger and Browning describe product architecture as “arrangement of components interacting to perform specified functions” [EB12:18]. Ulrich specifies this by defining it as a “scheme by which the function of the product is allocated to physical components” and more precisely as “(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specifications of the interfaces among interacting physical components” [Ulr95:420], cf. [UE12:185].

Besides the allocations of functions to physical components, other authors widen the scope of product architecture to the allocation to further product models. For instance, Kreimeyer defines product architecture as the mapping of requirements to components [Kre15:16]. Similarly, Yassine and Wissmann refer to product architecture “that maps functional requirements to physical elements or subsystems” [YW07:118]. Deubzer analyzes various approaches related to product architecture design and defines a framework consisting of various types of elements that can be mapped within the product architecture, for instance, requirements, (physical) components, working principles, functions, product properties, and lifecycle domains as possible viewpoints on a product [Deu15:63].

3) Product architecture as *commonality* within a product assortment

The third dimension of product architecture includes the consideration of commonalities of products within the product assortment. After Harlou a product architecture “is constituted by existing standard designs, existing design units, future standard designs and future designs. The architecture includes interfaces among the units and interfaces with the surroundings” [Har06:85]. Thereby, the distinction between *standard designs* and *design units* is made by whether the units are re-used in other products (standard designs) or not (design units) [Har06:92]. Accordingly, Martin and Ishii define the term *family architecture* as “common arrangement of elements, common mapping between function and structure, and common interactions among components. A product family architecture only exists if this commonality is present” [MI02:214].

Based on this consideration of commonality within a product assortment, various methodical approaches are connected to the product architecture, for instance, design for variety, platform design, and modular product design. These will be further considered within the section about principles for product architecture design, see Sec. 2.6.

General definition of product architecture

Considering these three dimensions of PA representation, product models can describe different viewpoints on the product architecture. These classes of product model are be referred to as *representations of the product architecture* in the following:

> **Definition: Representations of the product architecture**
> Representations of the product architecture (PA representations) describe the structures of elements within product models (e.g., function structures or component structures) and/or the allocations of elements of different product models (e.g., allocations between functions and component). The consideration of the product architecture can include only single products or include the commonality regarding several products within a product assortment.

This general definition includes the viewpoints of various authors. It shall be emphasized that these three dimensions of PA representation are *possible* viewpoints on a product. However, in most cases, it is not suitable to consider all viewpoints at the same time. Rather, for each specific design problem, a definition of suitable viewpoints has to be made, what will be shown within the following sections.

2.3.2 Classes of representations of the product architecture

According to the three dimensions defining the scope of the product architecture, several different representations of the product architecture are proposed in literature. These representations fulfill a specific purpose allowing to analyze specific product properties, as each product model does, see Sec. 2.2.1. Depending on the purpose of the context the representation of the product architecture is developed for, different dimensions of PA representation can be in focus of the representations while others are not included at all, compare [Ere96:8]. In the following, three examples shall be outlined that include each mainly one dimension of the product architecture. Further examples will be analyzed in Chap. 5.

The first example of a representation includes the dimension of the structure of a product by describing the product's working structure in the form of a *Geometric*

(Working) Structure. Roth proposes this representation for applying principles for function integration [Rot00:238], see Fig. 2.10, left. By visualizing working bodies (represented as long lines) and the interfaces between working bodies as working surface pairs (represented as two short parallel lines) the representation allows to focus on the central kinematic structure of a product. Roth proposes this model to support the identification of potentials of integrating working bodies as well as working surfaces for that he outlines basic principles. Similarly, various other models exist representing the product architecture by other kinds of elements, for instance, function structures (e.g., [Sto97:142]), effect structures (e.g., [Kol98:123ff.]), building structures (e.g., [Wie02:140]), or module structures (e.g., [Ble11:101ff.]). Moreover, *Design Structure Matrices* (DSM) can be used to systematically analyze and synthesize interfaces between elements, like functions or components, see [Ste81:72] [Mau07:54ff.]. All these representations have in common that elements of a product of the same kind (as elements of the same product model) are represented to be analyzed and synthesized with regard to specific product properties.

The second example includes the representation of allocations of elements of different product models. Therefore, Ulrich and Eppinger proposes the visualization of the function structure and building structure in comparison, see Fig. 2.10, middle, [Ulr95:421]. Within this representations functions are allocated to components, according to the definition of the product architecture of Ulrich and Eppinger, see above. By modeling these allocations, designers shall be enabled to identify suitable clusters of functions and components as organizational units, or, identify indications for changes within the function structure or building structure. Various authors use similar representations, e.g. [Rot00:235], [Rud98:255], and [Göp98:146]. Danilovic and Börjesson generalize this approach by defining *Domain Mapping Matrices* (DMM) as tools for mapping elements of different kinds [DB01:29f.].

The representation of commonality in the product assortment is shown in the third example by Caesar [Cae91:48f.], see Fig. 2.10, right. Therein, the components of a product family are depicted as boxes in their order of assembly from top to down. Those components that are variant, i.e., between those is chosen within the assembly process, are merged within one superordinate box. Therefore, the representations allow a clear overview of commonalities within the product family in contrast to variant components. Similarly, several other representations exist in literature highlighting variety, for instance, within a *Generic Billd of Material* of Jiao et al. [JTM+00:11], the *Modular Product Systematics* after Pahl et al. [PBF+07:496f.], and the *Product Family Master Plan* after Harlou [Har06:106ff.].

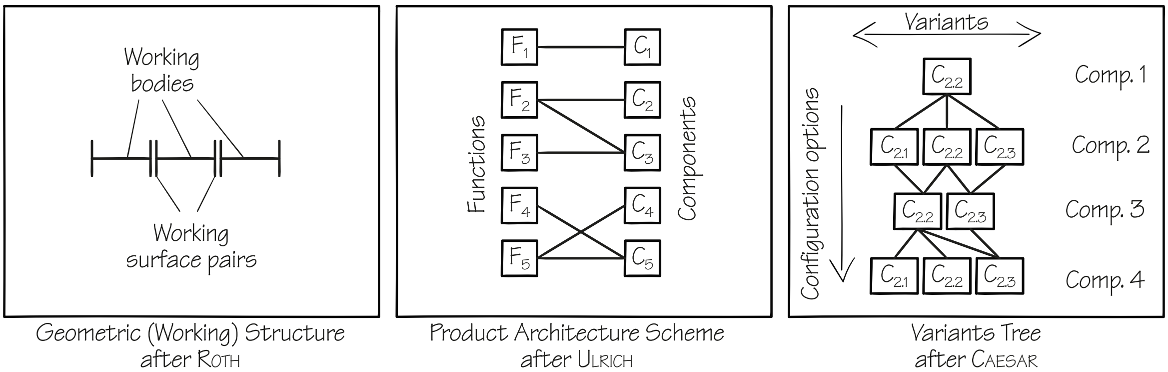


Figure 2.10: Different kinds of representations of the product architecture focusing on left: structure (after [Rot00:238]), middle: allocation ([Ulr95:421]), and right: commonality (after [Cae91:49])

The shown examples are selected to illustrate the three dimensions of PA representation. However, as mentioned, various other representations exist that consider various of the dimensions, for instance, representing *structure* plus *allocations* (e.g., in Polyhierarchical Interconnections [Rot00:46]), *structure* plus *commonalities* (e.g., in Generic Organ Diagram [Har06:119]), or *allocations* plus *commonalities* (e.g., in Variety Allocation Model [Kip12:79f.]). A detailed consideration of this will be conducted in Sec. 5.2.

2.3.3 Implementation of representations of the product architecture

A product architecture is inherent to each product since statements on structure, allocations, and commonality can be made for each product [Kvi10:53]. However, a representation of a product architecture that is used within designing is not actively used in each design project. In that case, the product architecture is determined *implicitly*. Therefore, in this subsection, it shall be reflected in brief how representations of the product architecture are included in product models used in designing.

First, it shall be considered how product models arise during a design process. In Sec. 2.2.1 and Sec. 2.2.2 it has been shown that in a design process different product models are used that can be allocated to specific stages, for instance, a function structure is used within the functional stage, cf. [Rot00:34]. In this way, a "chain of models" is generated in which product models are built based on the preceding models in order to increase the product description's concretization [Bir80:20]). Within this chain of models, the information about the product architecture regarding all three dimensions is included. Evidence for this is provided by the fact that existing PAD approaches take several different product models within the chain as basis, for instance, function structures, working structures, or assembly module structures.

Therefore, Wie et al. claim that an overarching notion of typically occurring representations of the product architecture can support designers to recognize which models shall be considered explicitly [WRC+03:32ff.]. Thus, they derive a notion of six possible product architecture representations: a *Spatial Constraint Diagram*, a *Function Layout Diagram*, a *Physical Solution Diagram*, a *Partition Diagram*, a *Manufacturing Diagram*, and a *Product Family Diagram*. By these notions, designs are enabled to implement product architecture considerations on the basis of six standard representations that are supposed to be easily derived from product models existing anyway within design processes.

Harlou chooses a similar approach by pointing out the relevance of considering the product architecture within different representations of the product [Har06:106ff.]. Therefore, he develops the *Product Model Master Plan* as a tool that includes three perspectives, see Fig. 2.11.

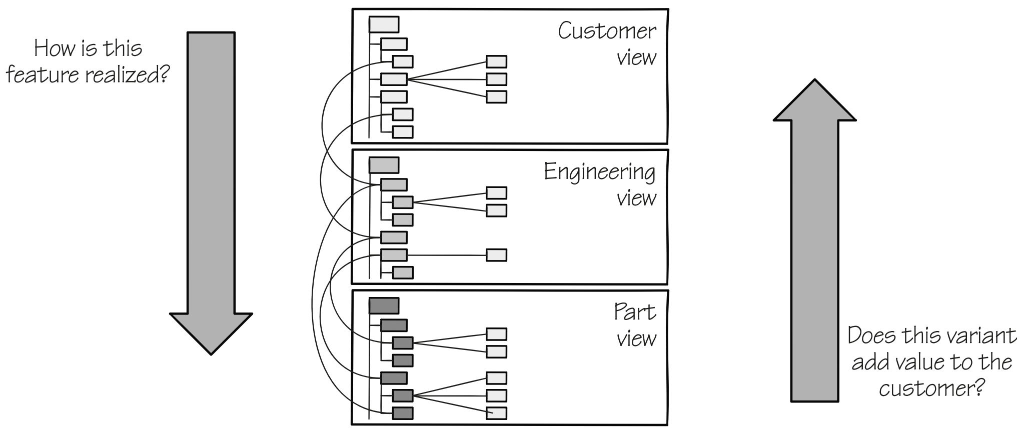


Figure 2.11: The *Product Family Master Plan* integrating the perspectives of the customer view, the engineering view, and the part view, and therefore, allowing a comprehensive consideration of the product architecture, adapted from [Har06:119]

The *customer view* including requirements and their relations, the *engineering view* including functions and their relations, and the *part view* including components and their relations. He argues that the models used within the three perspectives can be used for analyzing structure and commonality. Moreover, drawn relations in between the three view perspectives allow to analyze the allocations. Thus, when a company is enabled to integrate the three perspectives supposed to be existing in every company, a comprehensive consideration of the product architecture is possible.

Therefore, the implementation of representations of the product architecture is in many cases independent from the information existing about the product and closely linked to the definition of the design process since the design process defines the product models. This will be in focus of the following section describing how product architecture can be integrated into design processes from a procedural perspective.

2.4 Process integrity of product architecture design

Product architecture design can occur at various stages of a design process. To enable designers to integrate product architecture design at the most appropriate stages, the product models used in the processes play a central role. In order to understand these relations, in this section, first, an overview of the scope of the process of product architecture design will be given in Sec. 2.4.1. Subsequently, examples of processes will be described in Sec. 2.4.2 before, approaches will be presented that allow designers to decide on the integration of product architecture design into processes in Sec. 2.4.3.

2.4.1 Scope of processes of product architecture design

The term *representation of the product architecture* has been defined in Sec. 2.3 on the basis of the product characteristics included within the correlating product models. Accordingly, process models of product architecture design include the process characteristics like the activities carried out, the processed information, etc., see Sec. 2.2.2. However, aiming at a clear definition of processes of product architecture design, an deeper understanding of those process characteristics has to be developed.

Generic design processes like Guideline VDI 2221 [VDI93] describe the arrangement of activities within stages in accordance to used product models. Processes regarding product architecture design can be described in a similar way. However, a process of product architecture design cannot be delineated from the surrounding, general design process. The reason for this is that product architecture comprises a perspective on the product under development (see Sec. 2.3.3). Thus, when the product is continuously concretized within the design project, also the product architecture continuously develops. Therefore, product architecture design is not detachable from the activities carried out to design the product. Crawley et al. [CWE+04:2] highlight this by describing exemplary situations in that a product architecture “arises”:

- in the process of deliberating *de novo* a design of a system (since a product architecture is inherent to each product that is newly created)
- by evolution from previous designs with strong legacy constraints (when a new generation of a product is developed and the product architecture is taken over)
- by obeying regulations, standards, and protocols (for instance, when a product architecture strategy is defined by a platform)
- by accretion of smaller systems with their own architectures (for instance, when variants are derived from a modular product system by configuration)

The first situation describes that in each new product design project (as described in VDI 2221) the product architecture is defined at some point within the process. The other three situations highlight that product architecture design, in many cases, is related to the development of product generations or product variants. However, in each case, it is not seen as independent from the general design process. For this reason, the author of this thesis comes to following definition:

> **Definition: Process integrity of product architecture design**
> Process integrity of product architecture design describes the allocations of activities related to the determination of the product architecture to the design process – to stages for considering product architecture design (PAD stages). Therefore, product architecture design is not independent of, but part of overarching design processes.

Thus, in the following, product architecture design shall be regarded as a part of overarching design processes. The preceding subsection will show examples, of how it can be allocated to design processes.

2.4.2 Classes of integration points for product architecture design

The usability of existing PAD approaches is often limited to specific stages of a design process. However, in some cases, it is not clearly described at which stage within a design process and how the approaches shall be implemented [BGB+16:1185]. Therefore, the following examples shall emphasize the variety of possibilities of how existing approaches can be arranged in design processes.

One reason for the challenge of describing integration points of methodical approaches within design processes is that design processes are individual [Alb10:4]. Therefore, no process models exist that are actually generic. However, to demonstrate possibilities of integrating approaches, one established process model after Roth [Rot00:34] shall be taken to illustrate the challenge, see Fig. 2.12. Within the model, four stages are described: the clarification of the task, the function design, the conceptual design, and the embodiment design. To each of these stages, approaches are allocated based on the product models used. For instance, within the stage of the clarification, models describing the requirements on the product are used by designers. Accordingly, an approach of Renner [Ren07:130f.] can be used that supports the harmonization of requirements under consideration of variety. For the stage of function design, Stone [Sto97:108ff.] provides an approach based on function structures allowing to modularize the product within "early stages" of the design process. Thus, the advantage is seen in the fact that no information about the embodiment of the product is required. In contrast, Roth [Rot00:234ff.] proposes the application of principles within a *Geometric (Working) Structure* of the product. For this, the availability of principle solution is required and is seen as a suitable basis for carrying out operations of function integration. A precondition for the approach of Erixon [Eri98:65ff.] is the availability of a description of the technical solution. Therefore, the approach is applied within embodiment design aiming at identifying module candidates to be (re)designed as separated modules.

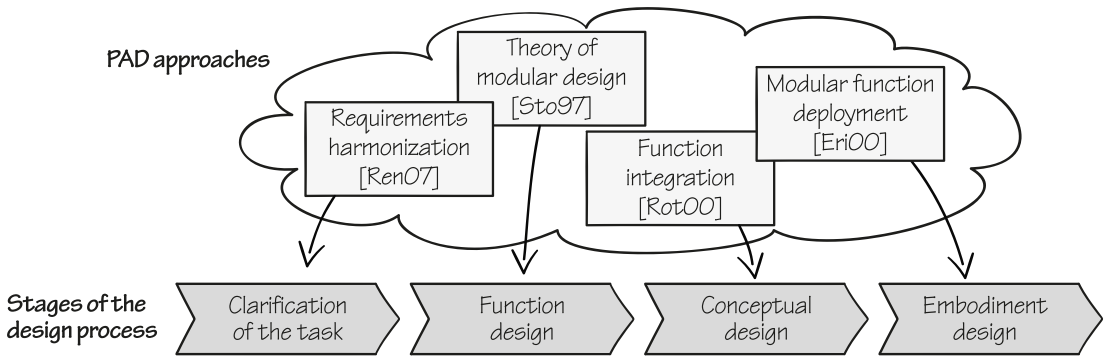


Figure 2.12: PAD approaches in allocation to the stages of the design process after Roth

Thus, the allocation of PAD approaches to stages of a design process presents a challenge for an appropriate integrability of product architecture design. In the following, concepts are described aiming at addressing this challenge by providing support for the implementation of approaches.

2.4.3 Implementation of processes of product architecture design

In literature some overarching frameworks exist that aim at facilitating the selection and process integration of PAD approaches. Thus, for instance, Otto et al. recognize a lack of structure for systematizing the variety of existing PAD approaches, in particular, for the design of platforms [OHS+16:1]. Therefore, they provide an overarching process model defining stages for platform design to which several different approaches are assigned in order to allow designers to overview and choose between them. Thereby, they distinguish, for instance, between approaches that are based on the functional description of the product and the descriptions of its components. Similarly, Firchau develops an overarching procedure for the design of product families that includes the description of various methods to be applied within specific stages [Fir03:124ff.].

A flexible approach for the integration of considerations of the product architecture provides Kipp [Kip12:95ff.], see Fig. 2.13. Therein, four levels of the concretization of the product are described. When elaborating concepts of a variety-oriented product, designers can decide whether the design activities shall be limited to the level of variant components. Then, an *adaptive design* process is carried out based on established working principles of the solutions. The effort for this adaptive design process is low since only one stage have to be carried out. However, alternatively, further levels respectively product models can be included into the consideration. Thus, further steps can include the redesign of the underlying (working) principles, the functions, and customer relevant properties of the product, compare levels in figure. In this way, the novelty of the solution can be increased resulting in a *new product design*. However, more effort has to be invested by carrying out these additional steps that must be balanced against the actual benefits that can be achieved.

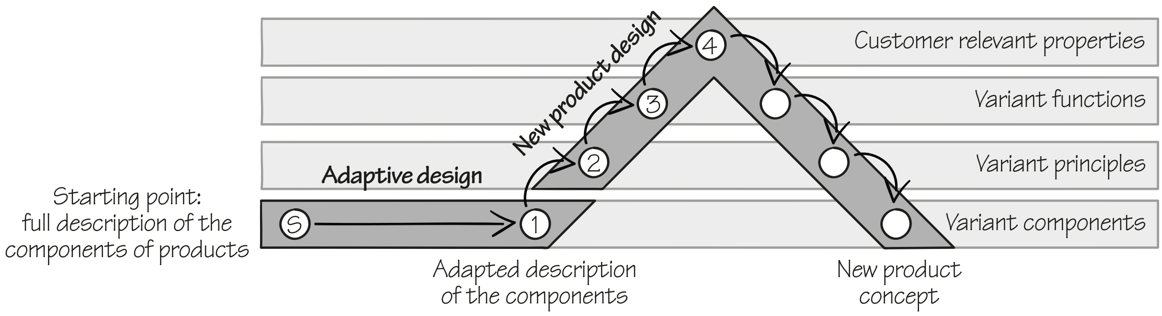


Figure 2.13: Stepwise incremental of the degree of novelty of product concepts based on the definition of stages to be carried out, adapted from [Kip12:96] [OHS+16:9]

In conclusion, the challenge remains that product architecture design can be implemented at different stages of a design process. Some approaches exist that point out the relevance of regarding the stages in which product architecture is considered. Thereby, the product models used within stages of design processes play a central role as indicators for the suitability of the consideration of the product architecture.

2.5 Goals for product architecture design

Within designing, *goals for product architecture design* (PAD goals) are defined to anticipate implications and define desired states of the product within different life phases. Within this section, first, the scope of implications will be outlined in order to define the term *PAD goals* in Sec. 2.5.1. Second, examples of classifications of PAD goals will be introduced to outline their range in Sec. 2.5.2. Finally, approaches will be described allowing designers to recognize implications of product architecture within design processes in Sec. 2.5.3.

2.5.1 Scope of goals for product architecture design

Sec. 2.2.3 has shown that design goals guide the designers through the design process by attracting attention to properties the product shall comply. Knowing the goals, corresponding design activities can be appropriately planned and carried out. Therefore, various PAD approaches are defined with a focus on specific goals (e.g., design for variety). The challenge within this thesis is to elaborate an overview of the various PAD goals. However, the effects of the product architecture on design goals are manifold and not clearly outlined in literature [YW07:119] [HK17:151]. This subsection attempts to give a brief overview of the scope of PAD goals described in literature.

Therefore, first, the difference between the terms *implications of product architecture* and *(design) goals for product architecture design* shall be regarded in more detail. Thus, *implications* (or *impacts*, *effects*) describe the actual perceptible consequences of the determination of the product architecture. For instance, a change of the product architecture towards a higher modularity may cause reduced robustness of the product due to more interfaces, but also a more efficient organization of labor during the product's development. These examples show that implications can be related to product properties (robustness) and process properties (development efficiency), see Sec. 2.2.1 and Sec. 2.2.2. A key task of designers is to anticipate these implications on properties and formulate a desired state of the properties as design goals. Therefore, the *goals for product architecture* define desired implications in order to influence these during design when the product architecture is determined.

Andreasen [And11:302f.] illustrates this interplay of PAD goals and PAD implications on the basis of the consideration of the product life cycle, see Fig. 2.14. Therefore, implications of product architecture are recognized within different phases of the product life cycle when different stakeholders (designers, manufacturer, users, etc.) "harvest the benefits" of a suitable product architecture. The challenge for the designers of the product architecture is to anticipate these potential implications and set them as goals. Examples for these goals entitled by Andreasen are *reducing complexity*, *handling variety*, and *establishing commonality*. Nevertheless, these formulated goals are rather abstract; they can provide designers an objective that is supposed to result in an optimization of implications of product architecture. For instance, when the product architecture is determined with a high commonality between several products within the company's portfolio, this may result in reduced development effort, simplified processes in distribution, and improved availability of spare parts when required during use.

These PAD goals only show examples considering a small number of possible implications of product architecture. Literature provides a large variety of possible PAD goals as well as the way of formulating these. Nonetheless, there is no common understanding of the full amount of PAD goals, authors generally agree on the fact that they relate to implications described as product properties, also referred to as "Design for X aspects"

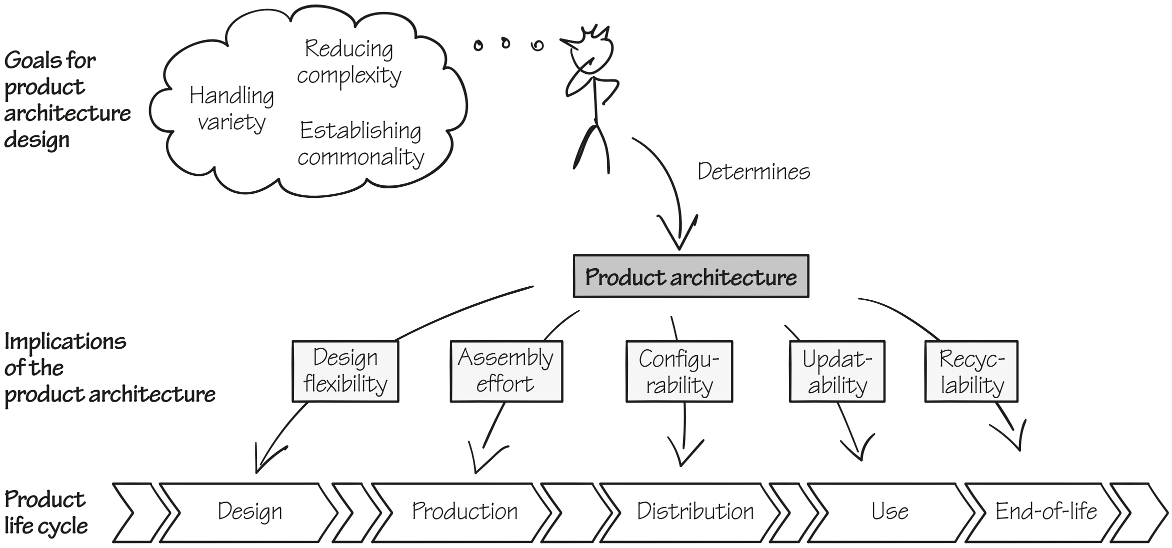


Figure 2.14: Implications of product architecture on different phases of the product life cycle, inspired by [And11:303]

[Deu15:18] or "ilities of the product" [CWE+04:2]. Therefore, PAD goals can be defined – according to the definition of design goals – as follows:

> **Definition: Goals for product architecture design**
> Goals for product architecture design (PAD goals) include those design goals described as preferred future states of product properties that are implicated by the product architecture within different phases of the product life cycle.

In order to provide a further understanding of the variety of PAD goals, the following subsection provides an overview of approaches to classify PAD goals.

2.5.2 Classes of goals for product architecture design

In literature, PAD goals are often described against a specific viewpoint. In many cases, authors provide effects of specific PAD approaches. For instance, PAHL et al. [PBF+07:356ff.] and KOLLER [Kol98:311f.] describe benefits and disadvantages of integral or differential designs. RENNER [Ren07:118f.] describes goals of platform design. SALVADOR [Sal07:221ff.] describes implications of modularization. ULRICH and EPPINGER [UE12:187ff.] describe implications of integral or modular designs on issues like product change, product variety, component standardization, product performance, manufacturability, and product development management.

Whereas these approaches highlight specific implications of product architecture design, other approaches aim at providing general classification schemes that shall allow designers to get an overview of PAD goals. Thereby, several authors focus on the product life cycle for classification, cf. [GPZ03:303ff.] [KG18:107] [Ble11:85ff.] [VS13:863f.]. In this way, the focus shall be expanded from the only consideration of *technical-functional* issues (mostly occurring in the use phase) to *product-strategic* issues (occurring in all life phases) [Ble11:68]. An often-cited basis for many of these approaches are *module drivers*, described first by Erixon [Eri98:72ff.]. These provide possible reasons for establishing modular product architectures within different life phases.

Another overarching perspective to product design is provided by approaches considering the management perspective of the company. Thus, Fixson describes implications of modularity within three domains of the company [Fix05:347ff.]: the *product (development) domain*, the *process domain*, and the *supply chain domain*. Deubzer highlights the consideration of issues related to decision-making, value networks, team organization, multiple project environments, and information/knowledge [Deu15:16]. Yassine and Wissmann allocate implications of product architecture to company areas within the dimensions *facets of the firm* (company, product, consumer) and *what is managed* [YW07:121ff.]. They summarize the results of their analysis within eight fields as illustrated in Fig. 2.15.

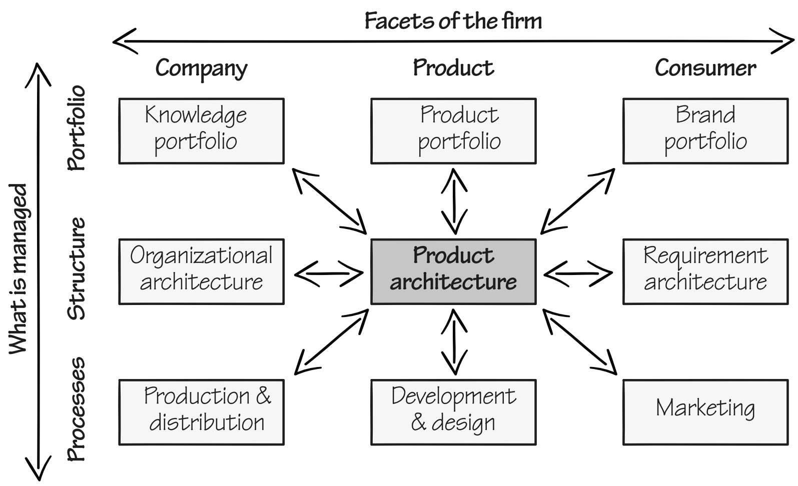


Figure 2.15: Implications of product architecture on the company, adapted from [YW07:122]

Other approaches focus on the interrelations between different PAD goals. Hackl and Krause, therefore, collate implications of modularity and visualize interrelations between the implications within and in between life phases [HK17:155ff.]. Ziebart describes implications of function integration and points out dependencies between the different goals [Zie12:154ff.].Therefore, both approaches highlight the importance of understanding the range of implications since a focus on only single implications may result in a negligence of side-effects.

In conclusion, various approaches exist pointing out PAD goals affected by the product architecture in different forms of classification. The different approaches provide specific viewpoints that allow to get an overview as completely as possible. In the following, the question of how those approaches can be implemented in design processes to allow designers to define and prioritize PAD goals shall be considered.

2.5.3 Implementation of goals for product architecture design

In order to enable designers to recognize the importance of the product architecture and to ensure its explicit consideration within the design process, implications of product architecture need to be defined as design goals. Therefore, many approaches in literature aim at supporting designers in the clarification of design goals with a focus on implications of product architecture.

Renner, for instance, highlights the importance of a recognition and prioritization of PAD goals within product family design [Ren07:118ff.]. He states that in platform development different goals can be in focus, for instance, reducing production cost, optimizing processes, optimizing the portfolio, increasing flexibility, or optimizing product performance. However, in many cases, only a few of these goals are in consideration of designers. Therefore, Renner proposes a diagram of possible goals allowing a prioritization as a basis for design activities.

Similarly, Erixon provides an overview of module drivers as indicators for PAD goals, as described above [Eri98:72ff.]. For assessing the relevance of the module drivers, he provides a tool called *Module Indication Matrix* allowing a pairwise comparison of module drivers and product components. In that way, each component is checked systematically for the relevance of specific PAD goals. On that basis, finally, a module concept can be elaborated that considers those goals correlated to parts of the product as module drivers.

Lange and Imsdahl [LI14:9ff.] base their approach on the module driver concept of Erixon. They state that module drivers (as tactic goals) shall be considered subordinated to value disciplines of the company (as strategic goals). Therefore, they allocate module drivers to the three value disciplines *product leadership*, *operational excellence*, and *customer intimacy*, see Fig. 2.16. In this way, designers are enabled to discern the strategic intention of a modular concept and to focus on most important value disciplines instead of considering modular drivers with a same prioritization. When goals conflicts arise, i.e., not all module drivers can be addressed at the same time, the focus shall be put on one of the three value disciplines and the module drivers included.

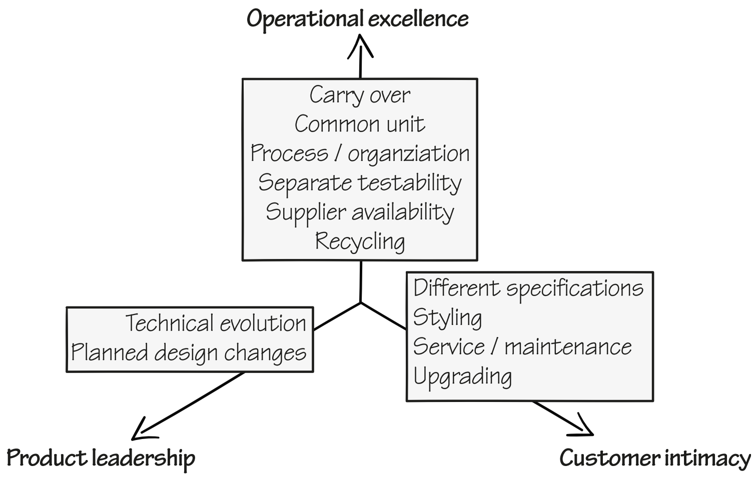


Figure 2.16: Value disciplines and module drivers, adapted from [LI14:12]

In conclusion, PAD goals are described in literature extensively. Several different schemes for classification as well as forms of formulation of the goals exist. This shows the importance of providing the knowledge about possible PAD goals to designers appropriately for allowing them to recognize the relevance of product architecture design and prioritize between different goals.

2.6 Principles for product architecture design

A central constituent of PAD approaches is the provided product-related knowledge. Within the first part of this section in Sec. 2.6.1, *principles for product architecture design* (PAD principles) will be defined as means for the formalization of this knowledge. Subsequently, the state of the art of principles will be briefly outlined in Sec. 2.6.2. Finally, approaches for the provision of principles to be implemented within design processes will be depicted in Sec. 2.6.3.

2.6.1 Scope of principles for product architecture design

As described in Sec. 2.1.3, the formalization and provision of knowledge is a central element of design research. Product-related knowledge was defined in Sec. 2.2.4 as *design principles* comprising a description of a specific arrangement of product characteristics as well as the implication on product properties. PAD principles comprise a subset of existing design principles describing specific arrangements of the product architecture. However, neither a coherent syntax for formulating PAD principles nor a clear delineation from general design principles exists in literature. This subsection will outline the scope of PAD principles in literature for a clear definition within this thesis.

PAD principles can be found in various approaches. In most cases, they are not presented in a listed form which would enable designers to compare them with principles of other approaches. Instead, the principles are incorporated within procedural instructions. For instance, Pahl et al. describe an approach for platform design [PBF+07:495ff.]. The approach consists mainly of a systematic of classes of modules and a procedure of six steps: (1) clarifying the task, (2) establishing function structures, (3) searching for working principles and concept variants, (4) selecting and evaluating, (5) preparing dimensioned layouts, and (6) preparing production documents. Within the procedure the product architecture-related knowledge is included only within text passages describing step 2 like "it is useful if [...] the overall function can be achieved by essential modules and by additional task-specific possible modules" [PBF+07:503] or "it is often more cost-efficient to combine several functions into one complex function" [PBF+07:503]. Whereas the first statement guides the designer to a separation of the product into modules, the second guides to integration of functions into few modules. Both can be regarded as PAD principles as they comprise knowledge about how the product architecture shall be arranged and how in this way specific goals can be achieved.

This example shows that in some cases it is not directly possible to extract PAD principles from approaches in literature. Wie recognizes this shortcoming in literature and formulates a need for "explicit information about what design variables shall be manipulated and the direction of those changes in order to produce a better architecture design" [Wie02:113]. Therefore, he and many others authors provide PAD principles structured in lists or tables (partly mixed with principles not related to the product architecture). In the following, some denominations of these are listed in order to show the variety of the different focuses of the approaches:

- guidelines for the development of variant products [KK08:428ff.]
- product development guidelines for flexible products [BB08:295ff.]
- design for changeability principles [FS05:346ff.]
- architecture design guidelines (focusing on modularity and flexibility) [Wie02:102ff.]
- fundamental possibilities for function integration [Rot00:239ff.]
- criteria for separation [Zie12:138f.] [EM13:502]
- design rules for function integration [Zie12:139ff.]
- types of functional designs (German: *Funktionsbauweisen*) [Kol98:307ff.]
- rules for integral and modular construction methods (German: *Integralbauweise, Modularbauweise*) [PBF+07:356ff.]
- types of modularity [PD99:201ff.]
- perspectives on product modularity [Sal07:221ff.] [KG18:90ff.]

Besides the denomination of principles, also the form of the PAD principles' description varies widely. However, the main constituents as described in Sec. 2.2.4 can be found in each of these principles: a statement on the design of the product architecture (resulting in a change within a PA representation, see Sec. 2.3) and on the implication on product properties (affecting the achievement of PAD goals, see Sec. 2.5). Therefore, within this thesis, PAD principles will be defined as follows:

> **Definition: Principles for product architecture design**
> Principles for product architecture design (PAD principles) are expedient representations of product-related knowledge containing statements on how specific designs of the product architecture implicate product properties, and therefore, contribute towards the achievement of design goals.

In order to provide an overview of PAD principles described in literature, the following subsection classifies some examples from existing approaches.

2.6.2 Classes of principles for product architecture design

As mentioned before, a clear structure for the systematization of PAD principles does not exist in literature. Rather, the description of many principles is based on terms for that clear definitions are missing in literature. For instance, the term *differentiation* is used for both the separation of parts of a product and the individualization of several products within a portfolio, cf. [PBF+07:356ff.] [Eil16:87]. Therefore, within this subsection, some fundamental terms will be defined based on literature. In order to provide a comprehensive overview and stay in line with the further thread of this thesis, a systematization is chosen that is in accordance with the defined three dimensions of PA representation, see Sec. 2.3: structure, allocation, and commonality. For each dimension, two general principles can be formulated constituting contrary design directions. The resulting six classes of principles are illustrated in Fig. 2.17.

In the following, for each of these classes of principles, one example is depicted, whereas the formulation is unified highlighting the change within the product architecture and the expected effect on design goals. Regarding the first dimension of PA representation – *structure* – two principles can be distinguished referred to as *integration* and *separation*:

- **Integration** (also referred to as: *consolidation*): Combining two or more elements within a product model (e.g., functions, components, modules) to one element, cf. [Rot01:412f.].

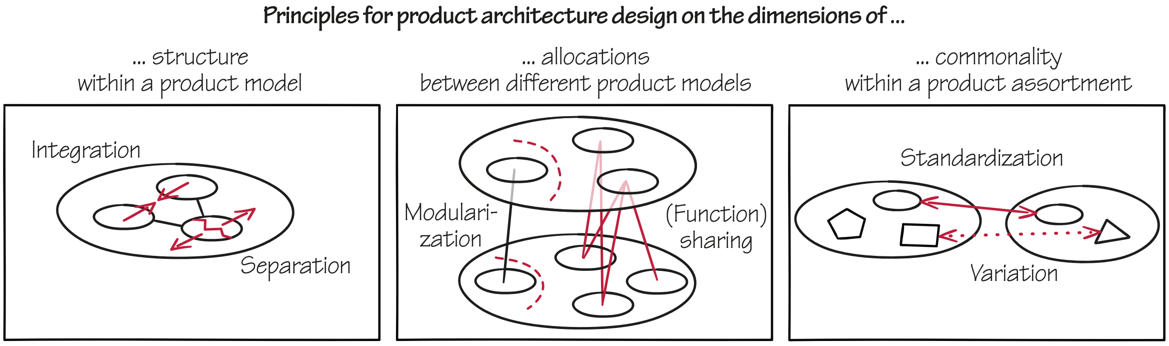


Figure 2.17: Classes of PA principles

Example: Integrating two working bodies into one working body that can fulfill the properties of both in order to reduce the number of parts, cf. [Rot00:239].

- **Separation**[4] (also referred to as: *differentiation*, *segregation*, *subdivision*, *modularization*): Splitting one element within a product model (e.g., functions, components, modules) into two elements, cf. [Rot01:413].
  Example: Separating one component (designated to be produced as one part) into two or more in order to facilitate production and reduce the overall product cost, cf. [PBF+07:356].

Regarding the second dimension of PA representation – *allocations* – two classes of principles are described in literature that, in most cases, refer to the allocations between functions and components based on the definition of product architecture after Ulrich, see Sec. 2.3.1. Here these are referred to as *(function) sharing* and *modularization* whereby it shall be noted that especially the term *modularization* is used in many different meanings in literature:

- **(Function) sharing**[5] (also referred to as: *n-to-n mapping*, *integration*, *coupling*): Drawing multiple allocations between functions and components resulting in functions that are realized by several components, and single components that contribute to the fulfillment of several functions, cf. [Ulr95:422].
  Example: Sharing one component for the fulfillment of several functions by exploiting its physical properties (e.g., electrical conductivity) in order to reduce the total number of components required for fulfilling all functions, cf. [US90:343].
- **Modularization** (also referred to as: *one-to-one mapping*, *decoupling*): Reducing the number of cross-links between components and functions to create decoupled units of components (modules) with no or few functional dependencies, cf. [Ulr95:422].

[4]The term *separation* is preferred to the term often used in the German community *differentiation* in order to avoid the risk of confusion with *differentiation* in terms of distinction.

[5]The term *sharing* is preferred to *integration* in order to avoid the risk of confusion with *integration* in the meaning of the opposite of *separation*, see above.

Example: Modularizing specific clusters of components (modules) by mapping specific functions only to these components in order to allow a separate testing of the functions, cf. [Eri98:72].

The dimension *commonality* is in focus when several products are considered within a product assortment. The classes of principles are referred to as *standardization* and *variation*:

- **Standardization** (also referred to as: *harmonization*, *normalization*): Aligning product characteristics of elements of different products to each other to normalize the product's handling within the product life cycle, cf. [Ren07:130f.].
  Example: Standardizing variant components by oversizing in order to reduce manufacturing cost caused by variant processes, cf. [Kip12:102].
- **Variation** (also referred to as: *differentiation* (of products on the market), *customization*, *individualization*): Creating different variants of an element to allow customers to choose between different product features, cf. [Eil16:86f.].
  Example: Varying components by allowing geometric fitting at installation (cut-to-fit) in order to provide high customization, cf. [PD99:201].

These examples only give a general overview of the variety of existing principles. Particularly, in Chap. 5 and Chap. 6 principles will be described in more detail and with an scheme for standardization. At this point, the further focus shall be laid on existing approaches to provide principles to designers within specific design projects.

2.6.3 Implementation of principles for product architecture design

Since there is no established approach for formulating and providing PAD principles, the way these are prepared for being identified and applied are very different within existing methodical approaches. However, as described in Sec. 2.6.1, various approaches exist that provide some kind of systematization. Reoccurring schemes for the provision of these principles can be distinguished between two groups: The first group systematizes principles regarding the product models respectively the stages of the design process. This ensures to apply the principles within an appropriate context regarding the available information about the product (see Sec. 2.3 and Sec. 2.4). The second group systematizes principles regarding the addressed goals independently from the product model or stage (see Sec. 2.5). In the following, some examples of these systematizations shall be depicted in brief.

By a systematization of principles regarding the product models or stages, designers are allowed to apply principles successively within the design process on the basis of different product models. In Fig. 2.12 it has been shown that product architecture design can be integrated into several stages of a design process. Therefore, principles can often be allocated to specific product models used within these stages. Kipp, for instance, provides a catalog of principles in four groups [Kip12:95ff.]: principles for *variant components*, for *variant principles*, for *variant functions*, and for *customer relevant properties*, see Fig. 2.13. The principles of each group are allocated to a specific product model and can be applied in the corresponding stage of a design process. Similarly, Bauer categorizes his list of principles to four hierarchical levels [Bau16:156,283ff.]. Ziebart defines stages in accordance to traditional approaches starting from the definition of function structures up to the embodiment [Zie12:23].

A categorization regarding the addressed goals shall allow designers to access principles for fulfilling specific product properties. Thus, various collections of principles can be allocated to categories of *Design for X* approaches as for variety, for lightweight design, for flexibility, for robustness, for standardization, for producibility, etc. However, some approaches provide principles for addressing several different goals. For instance, Bauer introduces (in addition to the before described systematization on hierarchical levels) a systematization of the principles according to before identified "sectors of primary directions of optimization" [Bau16:154,291]. Erixon provides principles based on module drivers that allow to distinguish various product-strategic goals [Eri98:72]. Hackl and Krause describe an impact model that allows to trace back effects of the product architecture on design goals within various life phases to basic principles of modularization [HK17:155ff.].

Especially based on the orientation of the principles provision according to specific design goals, more or less clearly defined strategies got established in literature for describing overarching guidelines for companies for product architecture design, cf. [KG18:134]. These strategies include several principles to be applied within different design projects in order to achieve the company's goals. Eilmus and Krause, as well as Krause and Gebhardt, therefore describe three strategies for establishing modular product structures [Eil16:23] [KG18:153]: The *platform strategy* poposes to use use modules of great size as basis for generating product variants within a product family allowing an efficient configuration of product variants. The *multiple-use* strategy aims at the standardization of small modules within the whole product portfolio of a company in order to reduce production cost by increasing the lot size of single standardized modules. The *module kit* strategy (German: *Modulbaukasten*) is constituted by a number of middle-size modules that allow to easily configure various product variants within and across product families. Each of these strategies is based on PAD principles that are applied during the design processes. Therefore, a determination of a strategy can manifest the use of principles for a defined time in the company within or across product families.

In conclusion, in this section, different types of PAD principles, as well as approaches for its classification and provision, have been shown. However, it remains a challenge to overview the principles' variety and find an appropriate systematization for specific design contexts.

2.7 Methods for product architecture design

Methods for product architecture design (PAD methods) comprise the knowledge about procedures for determining the product architecture. This section shall provide an overview of the scope of methods described in literature in Sec. 2.7.1. Thereafter, some exemplary methods will be categorized and depicted in Sec. 2.7.2. Finally, approaches on the implementation of design methods into design process will be outlined in Sec. 2.7.3.

2.7.1 Scope of methods for product architecture design

In accordance with the definition of design methods, see Sec. 2.2.5, PAD methods provide design knowledge in the form of procedures supporting product architecture design against the background of a specific purpose. The purpose of those methods is to achieve required process properties, for instance, the designers' work efficiency, or the development duration. However, in most cases, the key focus of PAD methods lies on ensuring the achievement of specific product properties. Thus, the main purpose of the application of both PAD methods and PAD principles for product architecture design is similar: ensuring the fulfillment of PAD goals, whereby methods provide the process knowledge and principles provide the product knowledge. Since in many cases both types of knowledge are required, they are often applied jointly.

As a product architecture is inherent to each product, see Sec. 2.3.3, within each design process, the application of various methods contributes to the determination of the product architecture. Therefore, it is difficult to distinguish between "general" design methods and PAD methods. For instance, the *Method of the Morphological Box* after Zwicky [Zwi67:285ff.] aims at identifying solutions (e.g., working principles) for problems (e.g., for realizing required functions). Therefore, by the application of the method, allocations of functions to physical elements of the product are determined, and as a consequence that they are mainly contributing to the definition of the product architecture. Nevertheless, in the common understanding, this method is not designated as a PAD method since it does not address explicitly specific PAD goals. In contrast, methods that focus on the achievement of design goals mainly affected by the design of the product architecture like standardization, reducing the number of parts, or handling product family variety will be referred to as PAD methods in this thesis, cf. [Wie02:4].

Similar to PAD principles, there is no unified structure for the description of PAD methods in literature. The core of the methods are procedures that, finally, allow designers to make well-founded decisions on the determination of the product architecture to achieve specific PAD goals. However, the focus of the methods can be laid on different activities. For instance, *Modular Function Deployment* by Erixon focuses on the clarification of the relevance of different product-strategic goals for components of a product [Eri98:65ff.]. The *Integration Analysis* by Pimmler and Eppinger mainly provides the *Design Structure Matrix* as a tool for the analysis of interactions between components for the elaboration of new concepts for clustering these components into modules [PE94:3ff.]. In his *Approach for Developing Flexible Products*, Bischof puts emphasis on the provision of synthesis-oriented guidelines including procedures for determining the product architecture within further considering a goal clarification of analysis of products [Bis10:83ff.].

Thus, PAD methods provide procedure for achieving PAD goals. According to the definition of design principles, PAD methods will be defined as follows:

> **Definition: Methods for product architecture design**
> Methods for product architecture design (PAD methods) are expedient representations of process-related knowledge containing statements on how specific activities concerning product architecture design implicate process properties (e.g., through providing rationales on the achievement of PAD goals).

In order to elaborate a further understanding of the PAD methods described in literature, a brief view on typical classes of methods shall be provided in the following subsection.

2.7.2 Classes of methods for product architecture design

The number and variety of PAD methods regarding their addressed PAD goals as well as their approaches to achieve these goals is great. Many authors have recognized the broad array of methods and the resulting challenge for designers to identify the most suitable methods, cf. [BHB+16:488] [OHS+16:1] [Zie12:144ff.]. For this reason, within this section, it is neither aspired to give an overview of all existing methods nor to pick specific methods out to be described extensively as it can be found in many review works on product architecture design. Rather, the objective is to provide a broad understanding of common approaches of fundamental classes of methods.

An established classification of PAD methods does not exist in literature. However, commonly used is a differentiation of methods regarding their addressed PAD goals, similar to the strategies defined in Sec. 2.6.3 grouping classes of PAD principles. Therefore, several types of *Design for X* methods can be described each addressing issues of product architecture design. Fig. 2.18 illustrates this qualitatively by representing classes of PAD methods by circles overlapping with product architecture design, and partly with each other, cf. [Zie12:35ff.] [Fir03:71ff.]. Three of these classes shall be considered in further detail, as these are often depicted in literature and seem to cover most PAD approaches from the subjective perspective of the author of this thesis: design for variety, design for modularization, and design for integration.

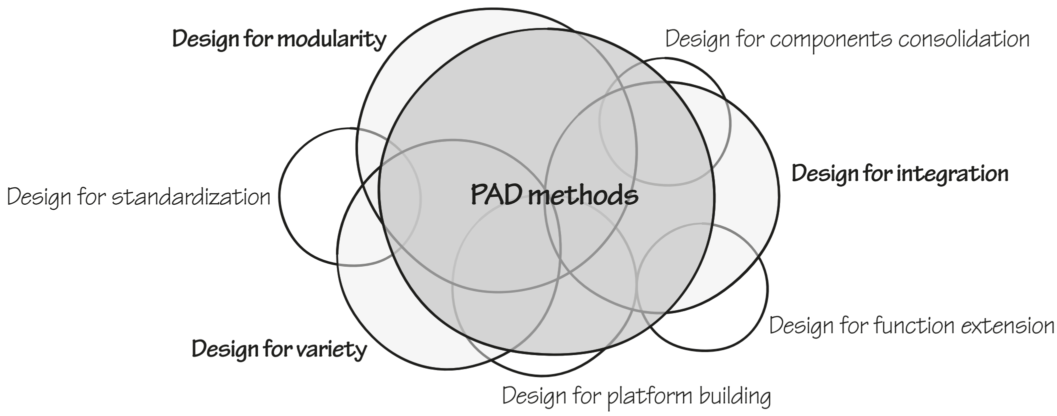


Figure 2.18: Qualitative illustration of examples of PAD methods overlapping

Methods focusing on design for variety comprise approaches for reducing the internal variety of components and processes in the company while ensuring an external variety in line with the market demand (the product variants offered by the company), cf. [KG18:33ff.]. Mostly, methods within this class comprise steps for gathering the existing variety within a portfolio and steps for elaborating product concepts that allow to configure many variants based on few reused modules [FS87:139ff.]. As basis for this, for instance, size-range products, modular product kits (German: *Baukasten*), product platforms, etc. are established whereby all kinds of principles can be applied, see Sec. 2.6.2. Examples for methods are provided by Franke and Schill [FS87], Kipp [Kip12], Pahl et al. [PBF+07], Caesar [Jes96], Jeschke [Jes96], Borowski [Bor61], and Harlou [Har06] to name only some.

Methods for modularization strongly overlap with methods for handling variety, since modular architectures can provide a basis for exchange components of the product for creating variants. However, variety-related issues comprise only a small part of the potentials of modularity that can have implications on the whole product life cycle [UFT+08:13]. Therefore, various methods for modularization have a clearly wider scope than methods focusing on design for variety, for instance, by considering issues regarding the organization of the development process or enabling reconfiguration within the use phase. Thereby, mostly principles for separation or modularization are applied, see Sec. 2.6.2. Examples are provided by Erixon [Eri98], Göpfert [Göp98], Blees [Ble11], Maurer [Mau07], and Eppinger [Epp02].

Methods for integration are often considered as aiming at the contrary of modularization in terms of *not* separating a product into modules, but aiming at integrated structures [EV97:8] [Ulr95:442], see Sec. 2.6.2. Thereby, most methods for integration focus on the reduction of the total number of parts of a product or the increase of the function scope of a product with unchanged number of parts, also referred to as *function integration* [Zie12:112]. Examples for those methods are proposed, for instance, by Ziebart [Zie12], Ulrich and Seering [US90], Roth [Rot00], Ehrlenspiel et al. [EKL+14], and Kalyanasundaram and Lewis [KL14]. However, since often designs decision have to be made for integration and contra modularization and vice versa, many methods combine modularization and integration. For instance, Erixon proposes to identify module candidates to be decoupled from modules, but also used as a basis for the integration of other similar modules [Eri98:109].

These three classes provide an illustration of what is meant by PAD methods within this thesis. However, again, it shall be highlighted that a clear delineation between the classes is not possible. Rather, the classes show that different topics overlap in product architecture design resulting in a need for the joint consideration of different approaches what is one of the main purposes of this thesis. Thus, in the following, it will be examined how existing approaches do provide support for implementing PAD methods into design processes.

2.7.3 Implementation of methods for product architecture design

The variety of existing methods described before, and the variety of possible integration points of methods into design processes (see Sec. 2.4) cause the challenge for designers to identify and implement methods appropriately. However, only a few research has been invested into the elaboration of frameworks for the situational provision of design methods in the context of product architecture design. In the following some examples of those frameworks shall be described in brief whereby two perspectives predominately define their structure (similar to the classification of PAD principles): First, the allocations of methods into the process, and second, their addressed PAD goals.

Regarding the process allocation, three approaches shall be highlighted from literature. First, Firchau proposes a framework based on general procedure for developing modular product systems comprising 33 steps within eight stages [Fir03:125ff.]. Within this extensive procedure, methods are listed to be chosen based on a short description of the purpose of the methods. Similarly, Otto et al. develop a *Modular Platform Definition Process* comprising 13 steps proposing alternative methods from different approaches in the field of platform design [OHS+16:2ff.]. Finally, Krause and Gebhardt establish the *General Approach for Modularization* comprising four steps: decomposition of the initial hierarchical product structure, analysis of the components, modularization of the selected level of consideration, and transformation into a new modularized product structure [KG18:130ff.], see Fig. 2.19. They state that several existing approaches for modularization can be allocated to this general procedure and propose methods for supporting each step.

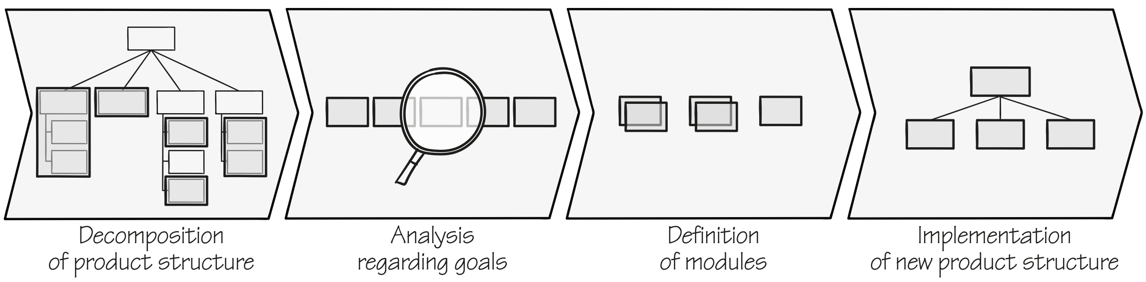


Figure 2.19: *General Approach for Modularization*, adapted from [KG18:130]

Other approaches base the provision of PAD methods on their addressed PAD goals. Ziebart, for instance, takes a goal model for function integration as a basis for the analysis of existing methods regarding their potentials to fulfill these goals [Zie12:114ff.]. In this way, a methods catalog is elaborated to enable designers to select methods for specific design situations. While Ziebart mainly provides already existing methods, the team around Krause at Institute for Product Development and Mechanical Engineering Design (PKT) at Hamburg University of Technology progressively elaborates the *Integrated PKT Approach* for the development of modular product families that is constituted by several method units [KBE+14:245ff.] [KG18:215ff.]. Each of the method units focuses on a specific PAD goal, for instance, reducing variety [Kip12], establishing a module structure under consideration of the whole life cycle [Ble11], or facilitating assembly [Hal14]. Therefore, this approach allows to select and combine method units appropriate for specific situations. Beckmann et al. provides a general approach for providing the method units included in the PKT approach and extends the approach for the description of further methods [BGB+16:1187ff.]. The approach comprises *description cards* of methods including the method's aim, procedure, tools and more. On this basis, designers are enabled to identify methods for the application within specific stages of a design process.

Thus, in summary, the variety of PAD methods is great. For some classes of methods, specific approaches have been developed allowing an identification of methods based on the considered processes or the design goals in focus.

2.8 Conclusion

The objective of this chapter was to provide an overview of the state of the art in design research regarding product architecture design. Therefore, at the beginning of the chapter, the scope of design research has been demonstrated with a model of design science adapted and extended from Hubka and Schregenberger in order to highlight the various facets that need to be considered in product architecture design. With help of this model, the scope of this chapter has been spanned by five key perspectives for the examination of the state of the art within the following sections. Thus, first, the fundamentals of product design have been described briefly by focusing on product models, process models, design goals as well as design principles and design methods. Thereafter, these five perspectives have been laid upon PAD approaches by outlining the key contributions regarding representations of the product architecture, the process integrity of product architecture design, goals addressed by the product architecture as well as principles and methods for product architecture design. By providing this overview, the range of existing approaches has been outlined in brief, and key terms have been defined for the use within the subsequent chapters. However, what the chapter could not provide is an extensive analysis of the existing approaches what will be further discussed in Chap. 5.

Besides the exposition of scientific fundamentals of product architecture design, the key insight of this chapter is that design research in general, and particularly, regarding product architecture design can be considered from different perspectives. However, the interrelations between these fields of research are often not obvious, for instance, how methods contribute towards specific design goals, or on what product models they are based. Therefore, many provided approaches for supporting designers focus on single perspectives neglecting other and complicating the overall understanding. Araujo describes this problem aptly as [Ara01:195]: "Lack of a unique framework for understanding product design tools represent a major bottleneck both for practitioners trying to take advantage of what is presently available, but also to researchers trying to investigate the topic." Facing this challenge, this thesis aims at providing such a framework for product architecture design.

Whereas this chapter focused on the theoretical view on product architecture design as described in literature, Chap. 3 aims at a further examination of the phenomenon of product architecture design in design practice. Based on this, goals for the development of the methodical approach elaborated within this thesis can be formulated.

3

Problem clarification

Factors for successful product architecture design

The previous chapter has outlined the manifold contributions of design research supporting product architecture design. However, observations in design practice lead to the assumption that, in many cases, designers are lacking an overview of methodical approaches existing in literature, see Sec. 1.2. To provide such an overview, a more detailed understanding of product architecture design within industrial practice is essential. Thus, the aim of this chapter is to gain deeper insights into the phenomenon of product architecture design in practice in order to clarify the assumed needs and refine the overall objective of this thesis. For this, the research approach will follow RQ-1 allocated to the *Descriptive Study I* of this thesis: *What factors within a product design process influence whether and by which supporting means the product architecture is considered in design practice?* The answer to this question will be elaborated within six sections as shown in Fig. 3.1.

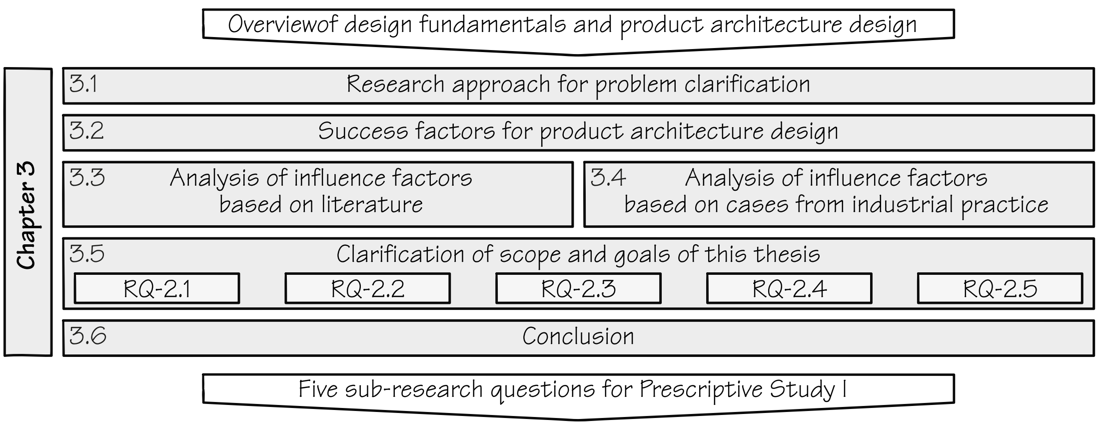


Figure 3.1: Structure of this chapter

Beginning with outlining the research approach for the task clarification in Sec. 3.1, the overarching success factors for product architecture design will be derived in Sec. 3.2. Based on this, in Sec. 3.3 a reference model is developed comprising influence factors determining the success of product architecture design. Subsequently, these factors will be validated and prioritized by an analysis of cases in industry in Sec. 3.4 upon which the goals of this thesis will be refined in Sec. 3.5. Finally, the chapter will be concluded in Sec. 3.6.

As a result, this chapter provides relevant issues that have to be addressed by a new methodical support to improve product architecture design. These factors provide a basis for the development of the methodical concept in Chap. 4.

3.1 Research approach for problem clarification

A design phenomenon is an "observable or imagined episode or articulation of designing" that is studied by researchers in design practice in order to improve it by the implementation of a methodical support [ABW15b:6] [BC09:16]. This section will describe the approach of how the phenomenon of product architecture design is studied within the *Descriptive Study I*. Therefore, first, the objective of the study will be specified in Sec. 3.1.1, second, the research method will be outlined in Sec. 3.1.2, and third, the study environment will be described in Sec. 3.1.3.

3.1.1 Objective of problem clarification

For understanding a phenomenon of designing, in general, two sources can be acquired: First, literature can be analyzed in order to find descriptions of other authors providing evidence on the design situation in practice. Second, the situation in practice can be analyzed directly, for instance, by observations or interviews with designers [BC09:80]. In the case of product architecture design, a lot of literature on the phenomenon exists. However, these sources often focus on very specific viewpoints on the phenomenon, for instance, only on specific addressed goals like reducing internal variety or specific stages within a design process when the product architecture is considered. In comparison, only few sources describe product architecture design comprehensively. The same applies for situations in design practice that can be observed by researchers: Although, many design projects in industry are related to product architecture design as it is considered at some point within the design process, it is difficult to gain an overview of the whole range of manifestations of product architecture design, i.e., to understand the variety of issues that may arise.

Thus, the challenge for understanding the phenomenon is to create an overarching understanding of product architecture design that is not limited to specific situations within the phenomenon but to describe various influence factors causing the variety of existing issues. Therefore, the key result of the *Descriptive Study I* should be a reference model according to Blessing and Chakrabarti including most relevant influence factors affecting the success of product architecture design [BC09:24ff.] that provides the basis for identifying the key issues to be addressed within this thesis.

3.1.2 Structure of the analysis

Within the study presented in this chapter, both named sources for gaining insights – literature and design practice – will be analyzed to derive and prioritize factors influencing product architecture design. Therefore, according to Blessing and Chakrabarti, the approach can be described in four steps [BC09:24ff.]:

1. **Determination of success factors**
   Based on theories of product design, an initial reference model is determined that comprises three *success factors* for product architecture design. These factors describe the ability of designers to determine "good" product architectures from an overarching perspective.
2. **Analysis of influence factors from literature**
   Existing PAD approaches are analyzed for assumptions on *influence factors* that are affecting the success factors and describe relevant issues on a level that can be considered within the design support directly. These influence factors and their interactions will complement the reference model.
3. **Analysis of influence factors within design practice**
   The identified influence factors are validated regarding their relevance within case studies of design projects in industry. Therefore, interviews with method experts and practice experts will be carried out.
4. **Definition of the scope of this thesis**
   The identified factors are clustered and prioritized in order to define the focus of this thesis.

In the course of research of this thesis, actually, these steps have been passed through iteratively, i.e., with returns to preceding steps. Thus, for instance, after having been identified the influence factors in design practice (step 3), these were evidenced by a more focused review of literature (step 2). Within this chapter, the factors will be described following the stated steps of the method in order to clearly distinguish between the sources of evidence.

3.1.3 Study environment

Due to the manifoldness of possible perspectives on the phenomenon of product architecture design and the specific researchers' roles, a subjective influence on the results of the study is hardly avoidable. Consequently, it is supposed that the author's background and the selection of case studies in design practice have a great influence on the thesis results. Therefore, the study's environment shall be described briefly in order to provide the reader a rough overview of the author's perspective.

The research work was defined by the projects that were in progress during the period of the author's employment at *Institut für Konstruktionstechnik* at *TU Braunschweig*. The thematic focus of this projects were divers varying in

- the project aim respectively the design goals in focus (e.g., developing in distributed environments or reducing variety),
- the type of product and company, and
- the role of the author within the projects (e.g., as a designer developing product concepts or as a method expert developing methodical supports).

On the basis of these differing aspects, an overview of the projects studied is listed in Appendix C. It shows that the project's scopes are varying from new product development projects to adaptive design or generation design projects whereas the addressed goals are in many cases related to variety. Aside from this, some projects focus on the design process organization, cost, or product size and robustness. The type of the products and companies varies from medium mechanical engineering companies to big companies within the automotive sector. The products are dominated by the domain of mechanics, whereas parts are included from electronics, software development, pneumatics, etc. The author's role was predominately to act as a method expert whereas in many cases he was also involved in the design activities.

Nevertheless, the focus of none of these projects was laid on an overarching understanding of the product architecture, the work was accompanied by an extensive review of literature and a consideration of the specific issues in industry against the scientific background of product architecture design. In many cases, this fundamental view on the projects showed additional issues, which, initially, were not in focus of the company. For instance, some projects defined clear design goals (like reducing variety) or approaches to be followed (like modularization). However, within the projects, other issues were identified (like the importance of robustness or weight) that lead to a wider consideration of the product architecture. Those examples will be further described in the initial evaluation of the results of this thesis in Chap. 7.

3.2 Success factors of product architecture design

Within the first step of *Descriptive Study I* general success factors of designing are defined. Therefore, implications of product architecture on the company's success will be analyzed in Sec. 3.2.1 from a generic perspective. Subsequently, measurable success factors will be derived in Sec. 3.2.2 that represent the immediate objective of the methodical support to be developed. Finally, in Sec. 3.2.3, the context of designing observed within this thesis will be outlined to provide a structure for further analysis steps.

3.2.1 Implications of product architecture design on the company's success

The company's success can be measured on several different levels. In order to allocate the scope of this thesis to the different levels, a brief view shall be put on an illustrative differentiation of the company's success made by Andreasen [And11:328f.]: On the top level, designing aims at the enhancement of the living standard of humans ("World class living standard"). Towards this, companies can contribute by performing a successful business within that they create new and innovative products ("World class business"). Besides sectors of the company like marketing and manufacturing, designing plays a key role in achieving a successful business ("World class designing"). The bottom level describes the design support, i.e., the immediate result of what is done within design research ("World class methods"). Thus, researchers have to decide on the levels they are focusing on.

For clarifying the objective of this thesis, the preceding chapter has described the achievement of design goals within product architecture design, see Sec. 2.5. Therefore, product architecture design affects a great variety of product properties, for instance, the product performance due to weight reduction, or the manufacturing cost due to a reduction of internal variety. Those design goals describe what makes a company's business successful since better products (with reduces weight or reduced manufacturing cost) get better sold or generate higher margins. Thus, product architecture design contributes to the "World class business" by allowing companies to offer better products to markets.

Accordingly, when influence factors on the success of product architecture design are derived in the following section, all these factors must be related to design goals. Obviously, the design goals can be detailed further, for instance, by considering how product architecture design leads to reducing weight or cost. However, at this point of this thesis all affected design goals shall be simply summarized under the umbrella term of the *quality of the product architecture*. Within the reference model, this term will represent the top level success factor of this thesis.

3.2.2 Measurable success factors of product architecture design

Therefore, the overarching aim of this thesis is to enable designers to increase the quality of the product architecture. However, to clarify the focus, this top-level aim has to be broken down to more specific success factors that can be measured more directly since the quality of the product architecture can only be measured over long-term studies. Therefore, a deeper look on the challenge of describing what makes a design process successful – including the determination of the product architecture – is required.

Regarding this question, various fundamental theories exist that provide models to describe the most relevant issues in designing. For instance, the ZHO model after Meboldt [Meb08:156ff.] as well as the CPM approach of Weber [Web07:86ff.], can be used to describe fundamental success factors of designing. Thus, the ZHO model describes designing as an interplay between the system of objectives, the system of activities, and the system of objects, see Sec. 2.2.3. The system of activities enables the connection between the system of objectives and the system of objects by providing support for analysis and synthesis. Similarly, the CPM approach describes designing as the transformation between product properties (similar to the system of objectives) and product characteristics (similar to the system of objects). Relations between properties and characteristics are analyzed and synthesized by means of design activities (similar to the system of activities), see Sec. 2.2.1.

Therefore, both models of designing include three central basic elements ("systems") of a design process. Each of these elements needs to exist in an appropriate form to allow designers to have success in designing. Assuming that these elements describing the success of designing in general can be transferred to the specific case of product architecture design, the following three success factors can be formulated to be addressed within this thesis:

- **Appropriateness of considered design goals** (according to the system of objectives): Designers require to understand the relevance of the implications of product architecture in order to formulate and address these as design goals within the process of designing.
- **Ease in deciding on the most suitable product architecture** (according to the system of activities): Designers require a sound basis for decision-making when determining the product architecture in order to address design goals.

- **Appropriateness of considered product information** (according to the system of objects): Designers require to consider an appropriate representation of information regarding the product architecture in the form of product modules including the product characteristics and the resulting product properties.

Accordingly Fig. 3.2 illustrates the initial reference model representing the described three measurable success factors as key influences on the quality of the product architecture defined within designing.

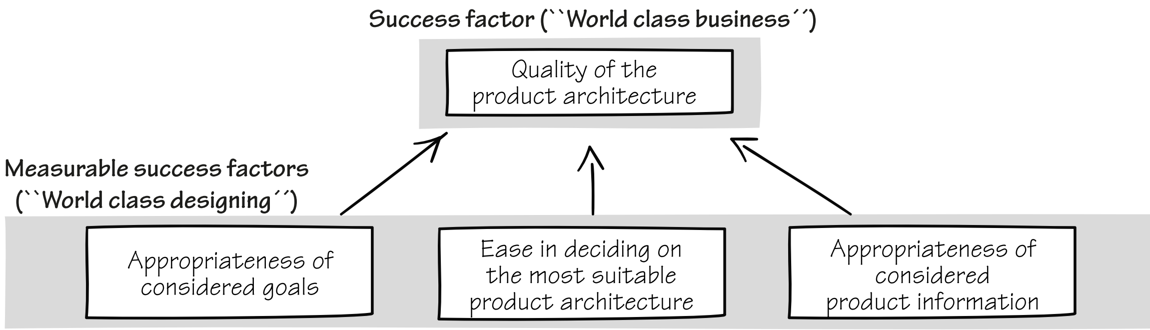


Figure 3.2: Initial reference model of product architecture design

3.2.3 Context of the phenomenon

In order to detail the initial reference model, further factors need to be identified influencing the three general success factors. Therefore, the context of product architecture design shall be observed in detail in order to provide a basis for the analysis of the phenomenon from appropriate perspectives.

Hubka and Eder describe designing as the transformation of information of an initial undesired state into a desired state [HE96:4], see Sec. 2.1.1. Within this process of designing various "operators" influence the process [HE96:4]. Araujo [Ara01:15] describes and interprets these as "elements of the product development process" that he defines as the *goals*, the *supporting means* (including design tools), the *information*, the *practitioners* (teams, designers, managers, etc.), and the *firm's environment*. According to this, the context elements for product architecture design shall be defined as follows:

- **Addressed design goals (G):** The design goals serve as the starting point for any design activity as they define the desired target state that is not fulfilled by the initial state of the product concept. The addressed design goals define the scope of the design activity and, finally, are the precondition for developing successful concepts.
- **Applied design support (S):** The basis for designers' decisions is the design support providing knowledge on relations between decisions to be made and the effects on

design goals. A design support can combine product knowledge (e.g., principles) and procedural knowledge (e.g., methods).

- **Available information about the product (I):** The object that is determined within the design activity is the product. During the design process, the information about the product appears in various different product models, each representing a different viewpoint on the product.
- **Aspects related to the designers (D):** The decisions on the product determination or the selection of design supports are made by designers. These bring in their own mindset, motivation, and competencies that influence the process.
- **Company's organizational environment (E):** The design activity is embedded in a greater environment consisting of the design team, the company, the cooperating companies, the customer, the legislator, etc. These elements impose various constraints on the design activities.

These five context elements are used in the following to precise the initial reference model by adding factors related to these. The letters in the brackets will be used as references to the context elements in the following sections.

3.3 Analysis of influence factors based on literature

The second step of *Descriptive Study I* aims at the derivation of influence factors within product architecture design from literature. The basis for this provides the initial reference model, see Sec. 3.2.2. The further analysis of factors influencing the success factors will be based on the context elements, see Sec. 3.2.3. The result of the literature analysis is illustrated in Fig. 3.3. It shows a simplified reference model according to the research approach of the DRM, see Sec. 1.4.

The reference model includes twelve influence factors that are assumed to have a direct or indirect effect on the three success factors of product architecture design. The colors of the success factors indicate their categorization according to the five context elements, whereas each category contains two or three factors. The directional links between the factors illustrate their assumed influences on each other. For instance, *designers' mindset* is assumed to influence *recognition of implication of the product architecture*, and, vice versa, a high *recognition of implications* may enhance *designers' mindset*. Furthermore, *designers' mindset* increases *availability of decision-support*, as designers are assumed to be more motivated to use methodical approaches. However, besides the drawn links within the reference model, further links are existing. For clarity, in the reference model, only those that are supposed to be most relevant are included.

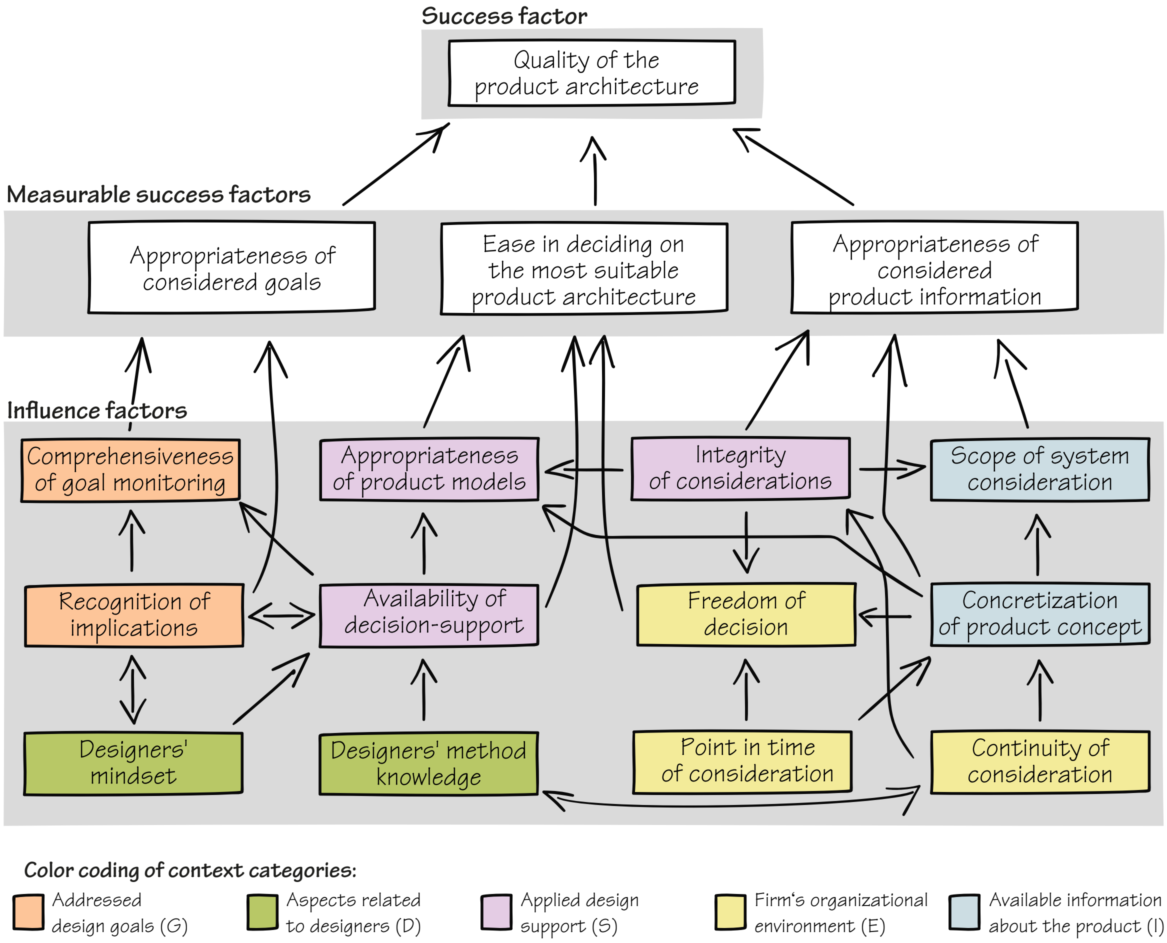


Figure 3.3: Reference model of the phenomenon of product architecture design

At this point within the thesis, the factors will be described only in brief to provide evidence for the most important aspects. Therefore, the factors will be described in the five blocks of the context elements. Further descriptions on the factors and their links can be taken from the detailed definition with references from literature in Appendix B.

Addressed design goals: Design goals guide the design process and define the scope of specific design activities, see Sec. 2.1.1. Therefore, their definition is crucial for any design activity. Regarding the success of product architecture design, two central influence factors were identified in literature: First, the *recognition of implications of product architecture* (factor G1) provides the precondition for understanding the relevance of product architecture design, whereas, second, the *comprehensiveness of goal monitoring* (factor G2) describes the continuous consideration of these within the design process. For further information see Appendix B.1.

Applied design support: During the design process designers make decisions when determining characteristics to fulfill required product properties, see Sec. 2.1.1. These decisions are based on the designers' understanding of relations between characteristics and properties, see Sec. 2.2.1. Design supports aim at increasing the designers' understanding of these relations. In this regard, *availability of decision-support* (factor S1), as well as the *appropriateness of product models* (factor S2) and the *integrity of PA considerations* (factor S3), were identified as relevant factors influencing product architecture design. See further in Appendix B.2.

Available information about the product concept: The information about the product is increasing during the design process due to a continuous concretization of the concept. Within specific design situation excerpts of this information are available in the form of product models in order to support specific decisions. For product architecture design, it is of high relevance to consider information of an appropriate *scope of the system* (factor I1) and an appropriate level of *concretization of the product concept* (factor I2). Further information can be found in Appendix B.3.

Aspects related to the designers: The impact of the human traits of designers on a design process is large, and various different properties of a design team can influence the success of a design process. Within this thesis, only two factors shall be considered in detail. First, the *designers' method knowledge* (factor D1), as their ability to apply methods, and second, the *designers' mindset* (factor D2) as a key aspect for proper use of methods within specific situations. For more details see Appendix B.4.

Company's organizational environment: The company's organizational environment comprises a number of factors with individual manifestations and relevance depending on the design project. *Freedom of decision* (factor E1) will be defined as an overarching factor comprising the limitations of choice when determining a product architecture. The factor *point in time of product architecture consideration* (factor E2) and *continuity of product architecture consideration* (factor E3) focus on the procedural allocation of the design activities within the design process. For further information see Appendix B.5.

To provide an overview of the twelve factors identified, for each of the factors, a problem statement was formulated as shown in Tab. 3.1. The problem statements describe the factors as hypothetical problems within a design situation. For each of these statements, a rating of the relevance can be made for specific design situation.

Thus, in this section, twelve influence factors have been described on the basis of literature. They provide the basis for understanding the main issues regarding product architecture design and will be used in the following to analyze design projects from industrial practice regarding needs for improvement.

Table 3.1: Problem statements regarding influence factors

Index	Influence factor	Problem statement
G1	Recognition of implications	Not all possible PA implications are recognized by designers resulting in a negligence of its consideration in the design process.
G2	Compreh. of goal monitoring	A comprehensive understanding of PA implications is missing during decision-making on product concepts resulting in an incomplete monitoring of design goals.
S1	Availability of decision-support	Designers are lacking required decision-support to determine a PA most suitable for defined design goals.
S2	Approp. of prod. models	Product models used to determine the PA are not appropriate for the assessment of defined design goals.
S3	Integrity of consid.	Product models proposed by PAD approaches lack an integrity to established product models used within design processes.
I1	Scope of sys. consid.	The scope of the product system considered by designers (subsystems of a product, products within product program) does not allow a maximum exploitation of potentials of PAD.
I2	Concretiz. of concept	The degree of concretization of the product concept when determining the PA does not provide a sufficient information basis for decision-making.
D1	Method knowledge	Designers are lacking the overview and understanding of existing approaches for PAD resulting in a missing or inappropriate utilization of existing design knowledge.
D2	Mindset	Designers do not believe in the value of PAD methods inhibiting a proper utilization of these in specific design situations.
E1	Freedom of decisions	The freedom of choice is limited due to organizational factors resulting in non-optimal decisions on the PA determination.
E2	Point in time of consid.	The point in time when the PA is explicitly considered for the first time is too late resulting in limited possibilities to take influence on the product concept.
E3	Continuity of consid.	The consideration of the PA is not continuously carried out within the design process resulting in a poor coordination of decisions on the PA determination.

3.4 Analysis of influence factors based on cases from industrial practice

Within this section, the influence factors are analyzed in industrial practice in order to substantiate the findings from literature. The aim is to gain insights from practice, whether the influence factors are seen as relevant in exemplary industry projects. In this way, statements on the importance of addressing the influence factors by a design support can be made. However, it is not part of this analysis to validate the links between the factors as shown in Fig. 3.3. In this section, the method of the analysis will be outlined in Sec. 3.4.1. Afterwards, the results of the analysis will be described and interpreted in Sec. 3.4.2.

3.4.1 Analysis method

Against the author's background described in Sec. 3.1.3, a validation of the influence factors can be achieved by an analysis of the industry projects accompanied by the author, see Tab. C.1 in Appendix C. As a suitable means for the analysis, interviews are selected for two reasons: First, interviews allow to achieve ratings of the twelve influence factors by other persons than the author of this thesis – even if an influence of the author on the interviewees cannot be entirely prevented since they were carried out by the author himself. Second, interviews can be carried out with a low effort for both the interviewer and the interviewees, while ensuring a shared understanding of the problem due to the possibility to discuss questions during the interview.

For each of the described projects, one interview partner was selected depending on their ability to overview the different factors. Each of the interview partners had been working in the company at the time when the design projects were carried out. They were involved in the execution of the design or were responsible for the design project. In each case, the interview partners as well as the design projects respectively the company was kept confidential in order to allow free answering of the questions.

At the beginning of an interview, the considered phenomenon of product architecture design was defined, i.e., a specific design situation was described to focus on during the interview. Typical design situations were, for instance, when a platform for a product family was defined, a modular concept was determined, or the consolidation of components was discussed. The aim of this limitation to one situation was to focus the rating of the factors to a specific phenomenon, rather than considering various different phenomenons that may occur within a company. A short description of the phenomena considered in the interviews are documented for each analyzed project in Tab. C.1. In the further course of the interview, each problem statement (see Tab. 3.1) was described by the interviewer and transferred to the defined phenomenon within a short discussion. Afterward, the interview partner stated a rating of the relevance of the problem statement within the considered phenomenon on a five-step scale from "top relevance" to "no relevance".

Indeed, the problem statements are short descriptions of in some cases very complex issues. Therefore, within the interviews, the problem statements were explained with the help of examples in the context of the considered project for ensuring a shared understanding of the factor.

3.4.2 Results from project analysis

The results of the project analysis based on interviews is shown in Tab. 3.2 by outlining the ratings of the twelve influence factors. The findings show a variety of the rating of the influence factors in between the different projects. For instance, the factor G1 (recognition of implications) is rated in Project P6 with *low relevance*, while in Project P2 it is rated with *top relevance*. Similarly, many other factors show a high spread of ratings over the projects.

Table 3.2: Rating of relevance of problem statements in design projects

Index	**Influence factor**	**Practice expert ratings**						
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**
G1	Recognition of implications	◕	●	◑	◕	◕	◔	◑
G2	Comprehensiveness of goal monitoring	◕	◕	◑	◑	◑	◑	◑
S1	Availability of decision-support	◑	◑	●	●	◔	◕	◕
S2	Appropriateness of product models	○	●	◑	●	◔	◕	●
S3	Integrity of considerations	◑	◕	◔	◕	◕	◔	◔
I1	Scope of system consideration	●	◕	○	◕	●	○	◕
I2	Concretization of concept	◔	●	◔	◕	◕	◔	◕
D1	Method knowledge	◑	◕	◔	◕	◔	◕	◑
D2	Mindset	●	●	◔	◕	◔	●	◔
E1	Freedom of decision	○	◔	◑	●	◕	◑	◑
E2	Point in time of consideration	◑	◕	◕	◕	◕	◔	◕
E3	Continuity of consideration	○	●	◔	◑	●	◔	◕

Legend: ● ≙ top relevance, ◕ ≙ high, ◑ ≙ medium, ◔ ≙ low, ○ ≙ no relevance

Overall, the results show that each influence factor is recognized with a high or top relevance in at least some projects while in other projects the same factor has only a low relevance. This spread of ratings across the projects highlights that depending on the design tasks different issues are in focus. However, the number of interviews does not allow to go deeper into analysis, for instance, by tracing the rating back to the industry sector or the experience of interviewee. Conceivably, these correlations are existing and its consideration would allow to develop more specific methodical supports. However, this is out of the scope of this thesis that aims on the development of an overarching framework, but not a specific methodical support.

Thus, since the number of analyzed projects, as well as the method of analysis, do not provide a sound basis for a quantitative conclusion of the findings, at this point it is waived to calculate the average value for each column and row since these values may mislead to a wrong conclusion regarding a prioritization. However, the results serve for providing evidence for the findings from literature. Even though, the analysis of influence factors in design practice does not allow to limit the scope of the thesis by limiting the number of factors to only a small group of relevant factors, the result highlights the relevance of the research topic. Nevertheless, it is inevitable to narrow down the focus of this thesis since it is not possible to address all factors to the same extent. Therefore, the following sections aim at discussing the results and deriving central issues that will be in focus of the development of a new design support.

3.5 Clarification of scope and goals of this thesis

The needs identified from literature and industrial practice show a broad distribution of issues that can be addressed within this thesis. In order to tighten the focus, this section aims at a convergence of the needs in order to focus the research on a manageable number of central challenges. Therefore, the identified needs will be classified regarding the fields of design research in Sec. 3.5.1, before the central challenges and related research questions will be derived in Sec. 3.5.2. Finally, a synopsis will show the focus on the needs within the thesis in Sec. 3.5.3.

3.5.1 Classification of influence factors regarding fields of design research

Within the preceding sections, a reference model has been elaborated and validated by interviews in design practice. In this way, twelve influence factors, as well as their relations to each other, have been identified. What shall follow now is a consideration of how these factors can be addressed by design research. The basis for this is provided by the fields of design research, see Sec. 2.1.3. Since these fields provide an overarching frame for different kinds of contributions to design research, an allocation of the influence factors to these can allow clustering the influence factors in order to be addressed by similar solution approaches.

Accordingly, Fig. 3.4 comprises a graphical allocation of the influence factors. The assignment of the factors is made according to the main questions addressed within the fields of design research. For instance, the first field *theory of products* aims at supporting designers in generating appropriate representations of the product for specific tasks. The need for *appropriateness of product models* (factor S2) can clearly be assigned to this field. However, for other factors the assignment cannot be made uniquely, i.e., single factors can contribute to various fields. For instance, the *integrity of considerations* (factor S3) can be addressed by the field of the *theory of products* as well as by the *theory of design* *processes*. The reason for this is, on the one hand, that the consideration of the product architecture requires support of product models that are consistently defined according to other product models used within the process. On the other hand, the processes must include the consideration of the different product models at the most suitable points in time and define the activities to transform the product models. Thus, only a comprehensive consideration of product models and process models allows a high *integrity of consideration*. Based on similar qualitative assessments regarding the focus of each influence factor, the author proposes a classification as shown in Fig. 3.4.

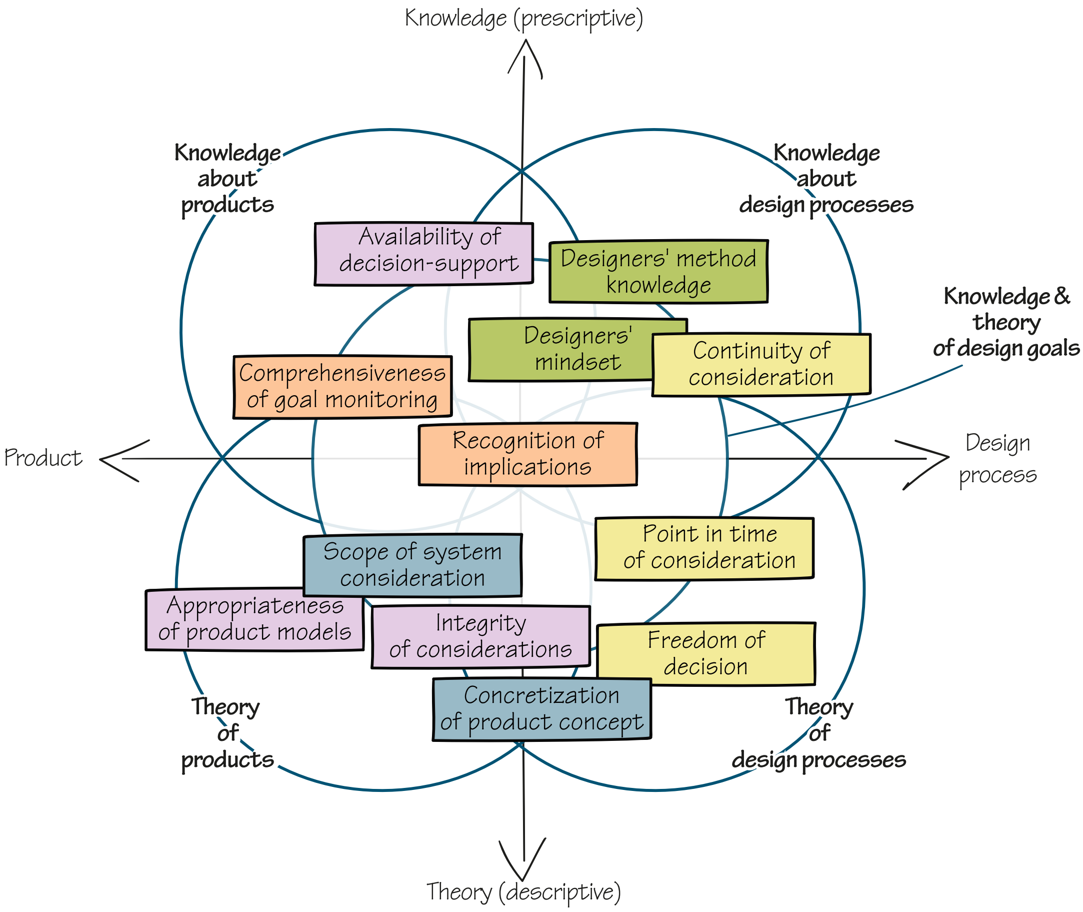


Figure 3.4: Allocation of influence factors to the fields of design research, see Sec. 2.1.3

In conclusion, it can be recognized that all influence factors can be allocated to the model of design research. Thereby, the factors are more or less evenly distributed throughout the fields of design research. This provides evidence for two statements: First, the model of the fields of design research is appropriate for describing the needs observed within the phenomenon of product architecture design. Second, for developing a design support to address these needs, the structuring of the support according to the fields of design research provides an appropriate basis to ensure a preferably comprehensive coverage. Thus, a support containing elements of all five fields of design research has the potential to address all needs. However, the results of the interviews in Sec. 3.4 have also shown that the need of companies can not be generalized, and the need of specific companies is often focused on a individual subset of influence factors. Therefore, depending on the industry sector of the company, the designers experience etc. the development of more specific supports can cover the needs more precisely.

3.5.2 Refinement of the research question for Prescriptive Study I

Within Sec. 1.4 RQ-2 was formulated in a very general manner for *Prescriptive Study I*: *How can designers be supported determining the most suitable product architectures?* The insights from this chapter allow to refine the objective of the development of a new design research by the formulation of more precise research questions. These shall be based on the five fields of design research since, in this way, a coverage of all influence factors is given, see Sec. 3.5.1. However, one factor that can be allocated to that field most apparently is in focus of each research question, see Fig. 3.4. Nevertheless, all other factors are addressed with a side focus to some extent what will be described in detail in Sec. 3.5.3. Accordingly, five subquestions each corresponding to one field of design research will be formulated in the following as subquestions to RQ-2.

The first questions, RQ-2.1, addresses the field of the *theory of products*. The main purpose of the question is on allowing designers to define most *appropriate product models* (factor S2). Therefore, as a central element, the representations of the product architecture will be defined as the specific class of product models. These will be referred to as "PA representations" in the following.

> **RQ-2.1: "Representations of the product architecture"**
> How can designers be supported defining the most appropriate representations of the product architecture (PA representations) to evaluate defined design goals?

The second question, RQ-2.2, addresses the field of *theory of design processes*. Its focus lies on the appropriate determination of a *point in time of considering the product architecture* (factor E2). The question concerns basically the definition of stages for considering product architecture design what will be referred to as "PAD stages" in the following.

> **RQ-2.2: "Stages for considering product architecture design"**
> How can designers be supported in deciding on the most suitable stages for considering product architecture design (PAD stages) within the design process?

The third question, RQ-2.3, is allocated to the field of the *knowledge and theory of design goals*. The question focuses on the support of the recognition of *design goals for product architecture* (factor G1). These will be integrated as goals for product architecture design into the design process that will be referred to as "PAD goals".

> **RQ-2.3: "Design goals for product architecture design"**
> How can designers be supported in understanding the variety and relations between goals for product architecture design (PAD goals) in order to elaborate the most suitable architecture concepts within specific design situations?

The fourth question, RQ-2.4, concerns the *knowledge about products* as a means for providing knowledge about designing "good" products. The central point of this question is to ensure the *availability of decision-support* (factor S1) for designers determining the product architecture. The question focuses on allowing access to principles for product architecture design that will be referred to as "PAD principles" in the following.

> **RQ-2.4: "Design principles for product architecture design"**
> How can designers be supported accessing and combining product knowledge as principles for product architecture design (PAD principles)?

Finally, the fifth question, RQ-2.5, is allocated to the field of the *knowledge about design processes*. The focus of this research questions lies in facilitating the methods' application by increasing the *designers' method knowledge* (factor D1). Thereby, the question concerns about methods for product architecture design that are referred to as "PAD methods" in the following.

> **RQ-2.5: "Methods for product architecture design"**
> How can designers be supported accessing and combining procedural knowledge as methods for product architecture design (PAD methods)?

These research questions provide the basis for the elaboration of the methodical concept to support product architecture design within the following chapter that will define the five hypothesis for improving product architecture design.

3.5.3 Synopsis of needs addressed within this thesis

In the preceding part, the research questions for *Prescriptive Study I* were defined according to the fields of design research, each question putting the main focus on one influence factor. In this section, it shall be recapitulated in which depth all other factors can be addressed within by the formulated research questions. Therefore, Tab. 3.3 shows a comparison of the influence factors with the five research questions. Within the cells, a rating is made to provide a qualitative estimation of the contribution of answers to the research questions for the improvement of the regarding influence factor. The rating was made by the author by a five-point scale from *not addressed* up to a *strong focus* of the research question on an influence factor.

Table 3.3: Correlations between influence factors and research questions

Index	Influence factor	Research questions				
		2.1	2.2	2.3	2.4	2.5
G1	Recognition of implications	◔	◔	●	◑	◔
G2	Comprehensiveness of goal monitoring	◔	◔	◑	◕	◔
S1	Availability of decision-support	◔	◔	◔	●	◕
S2	Appropriateness of product models	●	◔	◔	◑	◑
S3	Integrity of consideration	◕	◑	○	○	◔
I1	Scope of system consideration	◑	◑	○	○	◔
I2	Concretization of concept	◔	◕	○	○	◔
D1	Method knowledge	◔	◔	◔	◑	●
D2	Mindset	◔	◔	◑	◔	◑
E1	Freedom of decisions	○	◑	◔	○	○
E2	Point in time of consideration	○	●	◔	○	◑
E3	Continuity of consideration	○	◑	◔	◔	◕

Legend: ● ≙ strong focus, ◕ ≙ high, ◑ ≙ medium, ◔ ≙ low, ○ ≙ not addressed

From the table, it can be seen that the influence factors are addressed with different depths. For instance, the influence factor *appropriateness of product models* (S2) is addressed by RQ-2.1 with a strong focus. In the same way, the factors *point in time* (E2), *recognition of implications* (G1), *availability of decision-support* (S1), and *designers' method competencies* (D1) are assessed with a strong focus by RQ-2.2, RQ-2.3, RQ-2.4, and RQ-2.5 like described before. Furthermore, the table shows that each research questions puts a side focus on various other influence factors. In this way, all factors are addressed to some extent.

However, it becomes clear, that the claim of this thesis is not to improve product architecture design regarding all influence factors with the same focus. Instead, this thesis puts the main objective on the improvement of five factors, while the other seven factors will be addressed as secondary objectives. Even though, in this way, not all factors are addressed to a same extent, some key factors have been selected for focusing which allows to address relevant issues within each of the five fields of design research. In this way, a comprehensive support can be developed that provide the basis for extensions regarding a deeper consideration of the factors that are only addressed with a limited extent within this thesis. For instance, the factor *mindset* (E2) cannot be put in focus of this thesis. Nevertheless, the new design support shall highlight the relevance of product architecture design by RQ-2.3. In this way, a basis can be provided for carrying out training courses with designers in which they will elaborate a deeper understanding of the topic and be encouraged to expand the methods' use in design projects.

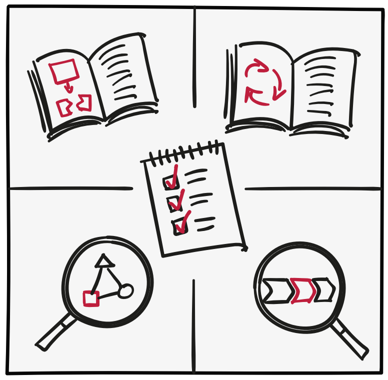
3.6 Conclusion

The aim of this chapter was to gain deeper insights into the phenomenon of product architecture design within practice in order to clarify the assumed needs and refine the overall objective of this thesis. Therefore, a reference model was elaborated illustrating factors influencing the quality of the product architecture. Besides three general success factors, twelve influence factors have been identified in literature. The analysis of industry projects supported by interviews with method experts and practice experts provided evidence on the relevance of all factors in at least some companies. However, depending on the company, the factors were rated differently. Finally, the influence factors have been categorized according to the five fields of design research introduced providing the basis for the formulation of five corresponding research questions to be answered in *Prescriptive Study I* in order to develop an general design support covering all five fields of design research.

The key insights of this chapter were provided by the identified needs from industry described by the influence factors. These substantiate the assumptions as formulated in Sec. 1.2 and allow describing the problem in more detail and decomposing it for an appropriate consideration within this thesis. Therefore, in the following chapters, the focus will be laid on five overarching challenges within the five fields of design research based on the five refining research questions. In this way, a clear structure for the framework can be established that is based on established theories from research. Within each of these five general challenges, an extensive review of existing approaches can be carried out for answering the question and provide a framework for existing knowledge regarding the defined five key elements:

- representations of the product architecture (PA representations),
- stages for considering product architecture design (PAD stages),
- goals for product architecture design (PAD goals),
- principles for product architecture design (PAD principles), and
- methods for product architecture design (PAD methods).

The research questions elaborated within this chapter will be answered, initially, by postulating hypotheses on the enhancement of the existing situation in Chap. 4. Therefore, fundamental design theories, as well as approaches from product architecture design, will provide the basis for an overarching framework allowing to systematize existing knowledge about product architecture design.



4

Methodical concept

Hypotheses on product architecture design

The preceding chapter has defined five key factors within designing influencing the success of product architecture design. An analysis of industrial practice has revealed needs for methodical supports to improve these factors. Based on that, five research questions have been formulated to precise the focus of *Prescriptive Study I*. This chapter aims at providing tentative answers to these five questions in the form of hypotheses. In this way, the phenomenon of product architecture design will be divided into five sub-phenomena. The corresponding hypotheses will provide five independent concepts laying the basis for the framework for product architecture design. Therefore, the delineation, separated consideration, and aggregation of the five sub-phenomena is organized by this chapter within four sections, see Fig. 4.1.

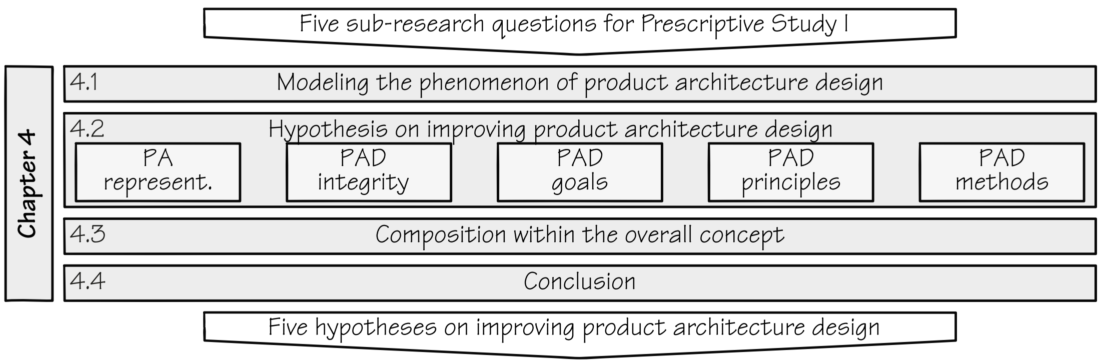


Figure 4.1: Structure of this chapter

As a starting point for the elaboration of the methodical concept, in Sec. 4.1 a phenomenon model of product architecture design will be established comprising the five sub-phenomena. Subsequently, in Sec. 4.2 for each sub-phenomenon a hypothesis will be postulated based on the needs identified within the previous chapter. A comprehensive consideration of the five hypotheses will follow in Sec. 4.3 by describing the composition of the hypotheses within the framework. Finally, the chapter will be concluded in Sec. 4.4.

The key result of this chapter is the postulation of the five hypotheses based on the phenomenon model. These will provide the basis for the classification of existing PAD approaches in Chap. 5, which serves in this way for a first substantiation of the hypotheses. Finally, the strains of the five hypotheses will be integrated within the comprehensive framework in Chap. 6.

4.1 Modeling the phenomenon of product architecture design

Despite the fact that many methodical approaches exist for product architecture design, the main challenge for designers is an appropriate application of these approaches in practice, cf. Sec. 3.5. In order to address the observed problems in practice, five research questions were formulated to specify RQ-2, see Sec. 1.4, and to provide a basis for the development of a new comprehensive design support. Within this section, an improved understanding of product architecture design shall be elaborated by describing a phenomenon model. Therefore, the phenomenon will be decomposed into five sub-phenomena in Sec. 4.1.1, before the phenomenon model will be described in Sec. 4.1.2. Finally, the general challenges within the sub-phenomena will be described in Sec. 4.1.3.

4.1.1 Decomposition of the phenomenon of product architecture design

In Sec. 3.1, in general, a design phenomenon was defined as an observable or imagined episode or articulation of designing. The phenomenon of product architecture design, initially, was manifested as all activities related to the analysis and synthesis of the product architecture, see Sec. 1.1. Within this section, a more differentiated consideration shall allow to understand and delineate several arising issues to be addressed, cf. [AHC15:43]. The basis for this approach provide Duffy and Andreasen [DA95:31ff.]. They outline the *Design Modeling Research Approach* proposing a procedure for developing new design supports. Accordingly, a central step within design research is the elaboration of a phenomenon model that includes those observations of the reality *that are relevant* for the employment and reflection of design tools. Solely based on this understanding of the phenomenon, researchers shall start the development of information models (e.g., by object-oriented modeling) and the transformation of these information models into new design supports (e.g., by computer tools).

In the case of product architecture design, the Research Questions formulated in Sec. 3.5.2 provide the basis for depicting the *relevant* observations within concerning the identified designers' needs. These are structured according to the five fields of design research introduced in Sec. 2.2. From these, a phenomenon model comprising five sub-phenomena can be derived. Based on this, information models and a new design support can be elaborated as will be done in Chap. 5 and Chap. 6, see Fig. 4.2.

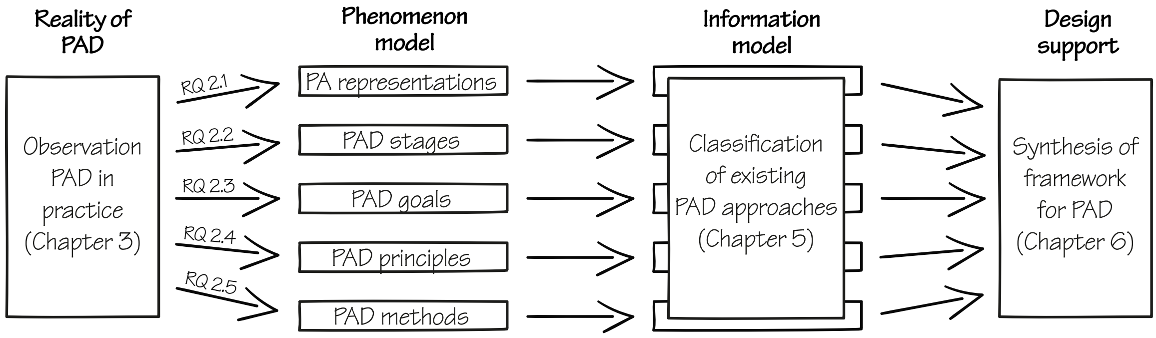


Figure 4.2: Research approach for developing a new design support based on the decomposition of the design phenomenon, structure according to [DA95:31]

Within the figure, the five sub-phenomena are named by the required elements of the phenomenon of product architecture design as described within the Research Questions: PA representations (RQ-2.1), PAD stages (RQ-2.2), PAD goals (RQ-2.3), PAD principles (RQ-2.4), and PAD methods (RQ-2.5). In the following subsection, these sub-phenomena will be described within the overarching phenomenon model.

4.1.2 Phenomenon model of product architecture design

According to the before described research approach, the basis for the observation of the phenomenon of product architecture design is provided by the Research Questions formulated in Sec. 3.5.2. These questions have in common that they target on enabling designers to define, access, or recognize specific elements that have been identified as relevant for the success of product architecture design in Sec. 3.3 and Sec. 3.4.

Fig. 4.3 illustrates the phenomenon of product architecture design as considered within this thesis. The composition of the figure is leaned on the general phenomenon of designing as a process of information transformation supported by the consideration of design goals and supporting means, cf. [HE96:8] [Ara01:15]. Accordingly, within product architecture design, the designers are processing information that is made available by a representation of the product architecture (illustrated as a magnifier representing a structure of a product). Since, in many cases, the product models are directly linked to a stage of the design process, each of the stages (arrows on the "floor") comprises a product model of a different kind. Product architecture design can occur within each stage. Within the figure, one instance of product architecture design is highlighted within one highlighted stage. As support for the designers within the product architecture design activities within this stage, three further elements are shown on an accompanying pinboard: goals that are considered and monitored (middle) as well as principles (left) and methods (right) providing prescriptive guidelines for the activities to be performed.

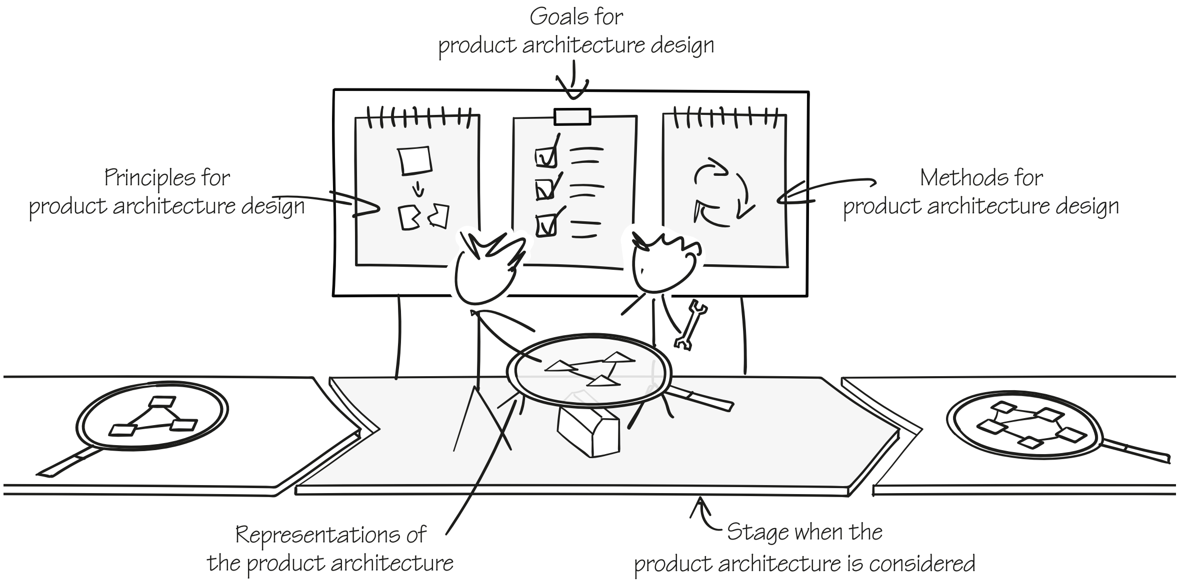


Figure 4.3: Phenomenon model integrating viewpoints of five research questions / hypotheses

The decomposition of the phenomenon allows to vary the focus of the observation of the phenomenon depending on the issues to be addressed. Thus, all sub-phenomena can be considered comprehensively when planning a design activity or developing a design support. However, in many cases it is not crucial to consider all, as some of the sub-phenomena do not require explicit methodical support. For instance, many existing PAD approaches focus mainly on single sub-phenomena like generating representations of the product architecture (e.g., [Göp98]), arranging a design process integrating the consideration of the product architecture (e.g., [OHS+16]), reflecting on the design goals (e.g., [Eri98]), providing product knowledge in the form of principles (e.g., [Rot00], or providing method knowledge (e.g., [BGK14]). The application of these approaches presupposes the clarity of the other sub-phenomena. However, in many contexts several sub-phenomena require support, and specific approaches may not cover these diverse needs.

Based on this decomposition, the phenomenon of product architecture design as considered within this thesis shall integrate all five perspectives in order to provide a comprehensive support. Therefore, following definition is constituted:

Phenomenon of product architecture design

Product architecture design comprises all activities related to the analysis and synthesis of the product architecture, i.e., the determination of appropriate structures, allocations, and commonalities of design units within different product models. Within these activities, following premises contribute towards the success of product architecture design:

- **Representations of the product architecture** (PA representations) are chosen appropriately to the design task.
- **Stages for considering product architecture design** (PAD stages) of the design process are chosen appropriately to the design task.
- Relevant **design goals for product architecture design** (PAD goals) are recognized and considered by the designers.
- Suitable **principles for product architecture design** (PAD principles) are available and appropriately applied.
- Suitable **methods for product architecture design** (PAD methods) are available and appropriately applied.

4.1.3 Challenge of integrating knowledge into the phenomenon model

On the way towards the development of such a comprehensive design support, according to the approach of Duffy and Andreasen described before, it is required to elaborate an appropriate information model first. This information model must include all information (e.g., principles, procedures, goals etc.) to be comprised by the design support in an appropriate manner, see Fig. 4.2. Thus, the following consideration focuses on the challenges arising when structuring the information according to the defined phenomenon model.

Generally, it is assumed that the knowledge required to support product architecture design is existing in various forms within literature. Chap. 2 has shown the variety of existing approaches, for instance, focusing on modularization, platform design, or function integration. From these approaches, the required information can be derived. However, in most cases, they are not structured according to the elements within the phenomenon model, and the single elements are not described in the same way. For instance, principles are described in the form of catalogs, definitions, or within the description of procedures. Therefore, the challenge in creating an information model is to provide an appropriate structure to integrate the existing knowledge from approaches into an overarching framework, Fig. 4.4.

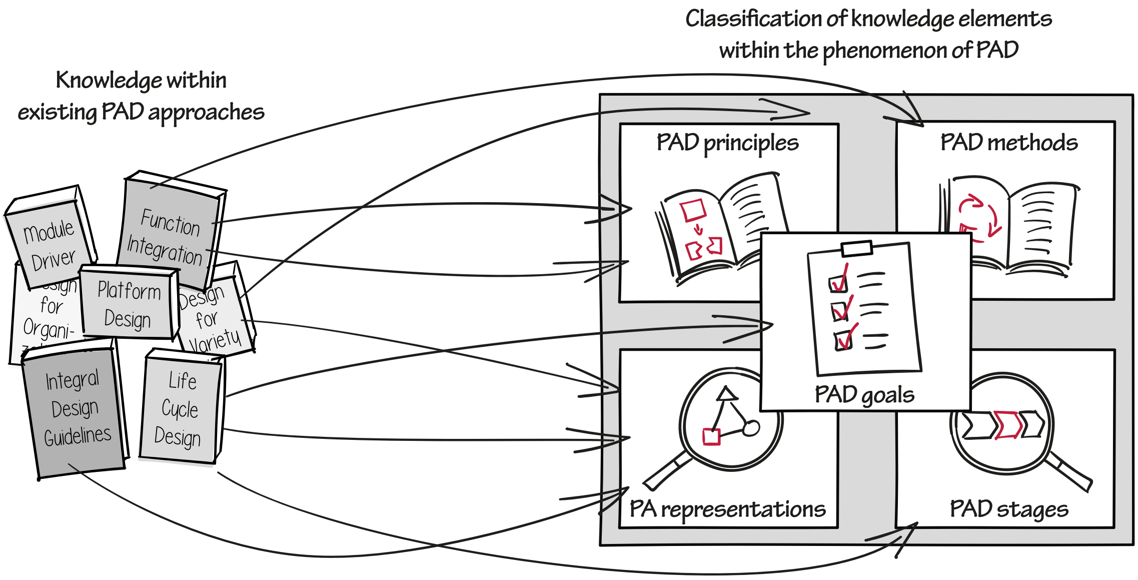


Figure 4.4: The general challenge of integrating existing knowledge from PAD approaches into an overarching classification scheme defined by the five sub-phenomena (compare arrangement of sub-phenomena with fields of design research in Fig. 2.3)

Thus, in the following, the five sub-phenomena of product architecture design will be examined regarding if there is a structure that allows to systematize the existing approaches. The formulation of five hypotheses aims at describing a scheme of a meta structure of the sub-phenomena, whereby a meta structure is regarded as an abstract description of all knowledge elements that can be integrated within the information model, cf. [Koh14:36] [Rag07:31]. Finally, these structures will provide the basis for the analysis of existing approaches in Chap. 5.

4.2 Hypotheses on improving product architecture design

The methodical concept of this theses will be built upon five hypotheses on how product architecture design can be improved. The hypotheses are tentative answers to the five research questions formulated within the *Prescriptive Study I*, each describing a sub-phenomenon of product architecture design. Within this section, the hypotheses will be derived against the background of the problems stated in Chap. 3. For each hypothesis (Sec. 4.2.1 to 4.2.5), in a first part, the relevance of the addressed subject will be described based on the state of the art shown in Chap. 2. Based on this, in a second part, a solution approach for the stated problems will be described by depicting a meta structure for systematization. Finally, the last part will outline the hypothesis as a basis for the subsequent classification of literature in Chap. 5.

4.2.1 Hypothesis 1: Representations of the product architecture

The first hypothesis aims at developing a deeper understanding of how PA representations are arranged and how designers can be enabled to identify those most suitable for their specific design tasks. Therefore, a tentative answer will be provided for RQ-2.1, see Sec. 3.5.2: "*How can designers be supported defining most appropriate representations of the product architecture to achieve defined design goals?*"

Appropriateness of PA representations

Product models are representations of the product (to be designed) comprising all information required within specific design situations, see Sec. 2.2.1. By providing the basis for analyzing and synthesizing relations between product properties and product characteristics, different types of product models can be used at different points in time within a design process depending on the properties in focus and the characteristics known [Bir80]. Thus a product model comprises only a specific viewpoint on information available and is appropriate for specific purposes [Buu90]. For this reason, several authors structure prescriptive models of design processes based on the product models used, e.g., VDI 2221 [VDI93].

Product models used for product architecture design contain a specific representation of elements of the product and their relations, for instance, representing the structure of product functions (e.g., [SWC00]), working structures (e.g., [Rot00]), or building structures (e.g., [Eri98]). Based on these representations, the product architecture is analyzed and synthesized. However, the variety of different PA representations proposed in literature is great and seems to be unlimited since for each purpose a different viewpoint on the product architecture can be suitable. Therefore, in Sec. 2.3.1, the product architecture was defined including three different dimensions – structure, allocation, and commonality – that can be included in a PA representation. The challenge for designers is to include the most appropriate aspects for a specific design situation.

This lack of clarity of how to represent the product architecture was identified in Sec. 3.3 as one key factor to be improved. Thus, it was described that in many cases the product models used within designing are not appropriate for the specific design task, i.e., the designated purpose of the product model does not comply with the desired purpose, see factor S2. This has an influence on the ease of designers in decision-making resulting in non-optimal product architectures. Therefore, an understanding of the differences between various PA representations is needed. Supported by such an overview, designers shall be allowed to select or generate representations appropriate for specific design situations.

Systematizing PA representations

The solution approach within this thesis aims at establishing an overarching framework to classify PA representations in order to allow designers to apply appropriate representations in specific design situations. Therefore, approaches for classifying product models, for instance, of Birkhofer [Bir11, Bir80], Ponn and Lindemann [PL11a], Andreasen [And11, And94], or Suh [Suh98] are followed, which differentiate between general types of product models according to their concretization, and therefore, their ability to represent specific product properties, cf. Sec. 2.2.1. For instance, Birkhofer [Bir80:21f.] classifies product models by the included characteristics as well as their properties.[6] Ponn and Lindemann [PL11a:33ff.] illustrates such a classification of product models on different levels of concretization as requirements models, function models, working models, and building models. Following these general approaches for product design, for product architecture design *basic PA levels* shall be defined that allow a generalization of characteristics and properties of specific instances of *PA representations*:

- **Basic product architecture levels** (basic PA levels) describe a set of possible viewpoints on the product architecture that can be used in design processes. The levels include information relevant for a defined set of design goals affected by the product architecture. Basic levels like function structures or building structures can occur in a design process in different ways and can be adapted to specific design situations.
- Specific **representations or the product architecture** (PA representations) describe particular instances of product models within the basic levels, which include information to support activities of analysis and synthesis of the product architecture. Most PAD approaches include some type of PA representations that comprise specific aspects of the product architecture according to the purpose of the approach.

Therefore, the basic PA levels provide a comprehensive description of possibly considered information about the product architecture. For most of all design situations, these PA representations comprise more viewpoints on the product architecture than required but allow to overview and set different viewpoints in relation in order to identify the scope of information appropriate. This necessity of considering different levels is already included in some existing PAD approaches. For instance, Kipp [Kip12] describes an approach for reducing variety comprising the levels of variant requirements, variant functions, variant working principles, and variant components. From these, appropriate levels can be chosen to apply principles for reducing variety.

[6] Birkhofer differentiates between "Elemente und strukturelle Merkmale" corresponding to *characteristics* and "Extensive Merkmale" corresponding to *properties*

Blees [Ble11] extends this viewpoint by adding the perspective of modules defined within life phases to exploit potentials through modularization. Otto et al. [OHS+16] highlight the use of a function-based and a component-based viewpoint within PAD approaches and demonstrate how these can be combined. Deubzer [Deu15] dissolves from established definitions of product architecture and describes different entities that can be included in the consideration of the product architecture like requirements, functions, effects, working principles, and components. Chap. 5 will define the levels used within this thesis based on a classification of existing instances.

Purpose of the meta level for PA representations

Within the framework for product architecture design to be elaborated, the sub-phenomenon of generating appropriate PA representations influences the appropriateness of considered information about the product architecture. The meta level described by the basic levels shall allow designers to better understand the variety of possible representations. Therefore, Hypothesis 1 defines one of five central premises of the framework for product architecture design:

> **Hypothesis 1: "PA representations"**
> The product architecture can be analyzed and synthesized based on different representations, each only representing a specific view on the product architecture, and therefore, being only suitable for a specific purpose. The definition of PA representations against the background of an overarching consideration of basic PA levels increases the appropriateness of product models used within the design process.

Up to this point, it has not been defined which basic PA levels are suitable for the classification. The definition will be elaborated by an extensive review of existing methodical approaches in Sec. 5.2 to ensure basic levels that cover all relevant instantiations of PA representations. This analysis will focus on the question on the differences of existing PA representations and, especially, the design goals then addressed.

4.2.2 Hypothesis 2: Process integrity of product architecture design

The before postulated hypothesis deals with the question of *how to represent* the architecture of a product. The second hypothesis aims at providing a deeper understanding of *when to integrate* this consideration into the design process. Therefore, an approach will be developed to give a tentative answer to RQ-2.2, see Sec. 3.5.2: "*How can designers be supported in deciding on the most suitable stages for considering product architecture design within the design process?*"

Appropriateness of stages for considering the product architecture design

Process models are used to represent the design process in order to understand the process properties and determine appropriate activities within the process, see Sec. 2.2.2. A central process property determining the success of a process constitutes the process quality to ensure the achievement of design goals. For instance, a process ensuring to develop light products in regard to the design goal of "reducing weight" represents an appropriate process. However, it is not possible to provide general descriptions of a design process that fit to each industrial context [Alb10:4]. Rather, it is important to understand when which information about the product is available and when specific design goals can be addressed. Therefore, for each design process it has to be defined individually when specific design activities are integrated into the overall process instead of prescribing specific stages, cf. [VDI18:1ff.].

Product architecture design describes one class of activities that can be performed within a design process. However, the kind of these activities are various, see Sec. 2.4. For instance, an activity of product architecture design can comprise the structuring of functions in order to define functional modules to allow further concretization in parallel for each module *early in the design process* (e.g., [SWC98:1]. In contrast, other activities focus on the integration of physical components in order to reduce weight or installation space what is only possible *late in the process* when the geometry of the product's components are defined (e.g., [EM13:502]). Therefore, the product architecture can be considered at different stages of a design process [CWE+04:2], and in many cases it seems hard to integrate product architecture design into design processes since a "coherent organizing structure" of existing approaches is missing [OHS+16:1].

Chap. 3 has identified this issue as a major bottleneck in transferring approaches into design practice since in many cases the points in time when product architecture design is integrated into the process are not suitable, see factor E2. One central consequence of this is that the freedom to define the most appropriate product architecture, see factor E1, as well as the concretization of information available, see factor I2, is non-optimal. Thus, it is important, to find a process-oriented systematization of approaches to allow an integration into design processes at the most suitable time.

Systematizing processes regarding the consideration of the product architecture

Due to the individuality of design processes, the solution approach within this thesis does not aim at an explicit allocation of specific product architecture design activities into design processes (e.g., *early* or *late* in a specific process). Rather, designers shall be enabled to elaborate a task-specific understanding of design processes to be able to define the most suitable integration points by own considerations of the appropriateness. This approach follows current research approaches that describe general models of the design process with a high integrated flexibility, cf. [ABW15a], [Pon07], or [VDI18] (in contrast to outdated approaches like [VDI93] or [PBF+07] that provide rather fixed procedures). Therefore, within the approach, design processes shall be described by generic design stages that are defined by the product models used. These generic design stages shall be transferable to different kinds of design processes and provide an overarching modeling formalism for them. In Sec. 2.2.2, this approach was shown by Gericke et al. [GBG+10:11]. They analyze design processes by allocating its stages to generic design states like *need*, *problem*, *requirements*, etc. According to this idea, it is also supposed for product architecture design, that basic design stages allow to classify specific activities related to product architecture design in order to enable designers to integrate them into individual design processes at the most suitable point in time. Thus, the abstract *basic design stages* will be distinguished from the *specific stages for considering product architecture design*:

- **Basic design stages** describe unspecified, generic stages within design projects that are defined by the type of handled product models, for instance, function models, working structures, or building structures. Depending on the specific context within design projects, the basic design stages can be passed in different orders.
- Specific **stages for considering product architecture design** (PAD stages) describe specific instances of basic design stages in which the consideration of product architecture is integrated into the design process. The basis for this provide the addressed design goals and the available information about the product architecture in the form of product models.

This approach of differentiating between levels of process description is also found in literature of product architecture design. For instance, Firchau [Fir03] depicts a modular set of methods for platform development within a general procedure, Otto et al. [OHS+16] provide a toolbox for modularization in accordance to a process model derived from practice, or Ziebart [Zie12] allocates approaches for function integration into the basic stages of VDI 2221 [VDI93]. However, a coherent understanding of overarching basic design stages appropriate for all of these approaches does not exist.

Purpose of the meta level for PAD stages

With the definition of basic design stages, an unspecific description of design processes can be elaborated that provides the basis for the integration of product architecture design. In this way, designers shall be enabled to understand the central characteristics of design stages: the used product models. Based on that, they can decide when to integrate product architecture design respectively define specific stages for considering product architecture design. Therefore, this approach is closely linked to Hypothesis 1 regarding the available information within a process. Accordingly, the underlying assumption regarding the process integrity of product architecture design will be postulated as Hypothesis 2 for further validation within this thesis:

> **Hypothesis 2: "Process integrity of product architecture design"**
> Decisions on the product architecture can be made at several points in time during the design process depending on information available and decisions to be made while concretizing the product concept. The understanding of basic design stages within a design project including the consideration of available product models increases the designers' ability to allocate product architecture design to the most suitable stages of the design process (PAD stages).

Within this section, the description of the hypothesis only outlines the basic idea of the approach. Within an extensive literature review in Sec. 5.3 methodical PAD approaches will be analyzed regarding their specific boundary conditions to be integrated within processes. On that basis, a general understanding will be developed allowing a formulation of basic stages of design processes being suitable to fulfill the hypothesis.

4.2.3 Hypothesis 3: Design goals for product architecture design

Within the first two hypotheses, it was outlined that decisions on PA representations as well as the points of time when they are considered within the design process are often strongly connected to the design goals, i.e., the properties that a product shall fulfill. Thus, the third hypothesis aims at answering RQ-2.3, see Sec. 3.5.2: "*How can designers be supported understanding the variety and relations between goals for product architecture design in order to elaborate the most suitable architecture concepts within specific design situations?*"

Recognizing design goals affected by the product architecture

Properties describe the behavior of the product in its environment in different life phases, see Sec. 2.2.1. A central challenge in a design process is to anticipate the behavior of a product and formulate the desired behavior by defining required properties. Those required properties guide the design process serving as design goals against which the designer evaluates his/her activities, see Sec. 2.2.3. Thus, the formulated design goals provide the basis for determining the product and process as well as for accessing design principles and methods for the specific design task.

As the product architecture affects a great range of product properties its determination has implications on the fulfillment of various design goals, see Sec. 2.5. To give only some examples, integral designs can result, for instance, in savings of product costs or the reduction of weight and installation space [Ehr09, US90, Zie12]. Modular designs, in contrast, can be applied in order to enhance changeability or allow the efficient configuration of product variants [Eri98, GPZ03, Sal07]. However, in many cases, various design goals have to be balanced when the product architecture is defined since goal conflicts can arise. Erens and Verhulst, for instance, describe modularity and integration as “contradictory requirements” [EV97:8], and Blees highlights the conflicts that can arise in between concepts for modularization focusing on different life phases [Ble11:18f.]. Therefore, in product architecture design, it is of high importance to be able to overview and assess implications of design decisions.

Chap. 3 provided evidence that the appropriateness of the considered design goals within product architecture design is a major success factor. It was identified that often implications of product architecture are insufficiently recognized by designers, see factor G1. Moreover, designers are not aware of the interrelations between the fulfillment of specific goals, see factor G2. This leads to a negligence of the importance of the product architecture within designing or a lack of a founded basis for decision-making resulting in non-optimal product architectures.

Systematizing design goals for product architecture design

The solution approach aims at elaborating a comprehensive goal model including most relevant implications of product architecture being addressed within established methodical approaches. Therefore, a systematization of design goals regarding their effect to superordinate strategic design goals shall be established in order to widen the viewpoint of designers onto their design projects. This approach is established within various other fields of design. For instance, for gathering and managing requirements, approaches are applied to systematize goals regarding their importance for different hierarchy levels of the company from the strategic to the operative level, cf., [Bad07, Ste10]. Other approaches, for instance, [Ost04, PML11] start the definition of goals with an extensive analysis of the user involvement within the company and develop business models before defining specifications on the product. In this way, they start to define business goals as a basis for defining goals for the development of the product. Thus, all these mentioned authors differentiate between two levels of goals. Accordingly, it is assumed that also goals goals affected by the product architecture can be regarded from a strategic viewpoint of the company, before they are braked down to the level of goals for product architecture design.

- **Strategic design goals** describe the idea of a company of how to offer value to its customers. Therefore, overarching aims are prioritized, for instance, described by product quality, time-to-market, and cost.
- Specific **goals for product architecture design** (PAD goals) describe product-related instances of strategic goals and comprise the description of a desired state of product properties that serve for fulfilling the strategic goals, for instance, functionality, weight, or robustness. Design goals can be affected directly by the determination of the product architecture.

Various methodical PAD approaches exist that explicitly or implicitly differ between different levels of goals. For instance, Lange and Imsdahl [LI14] describe goals for modularization as a "tactical vehicle to convey the business strategy" due to product leadership, operational excellence, or customer intimacy. Renner [Ren07] illustrates different strategic thrusts within a spider diagram to allow a prioritization of goals for platform development. Erixon [Eri98] established an approach to classify "module drivers" addressing specific design goals within different life phases. The challenge within this thesis is to elaborate an appropriate structure of strategic goals that allows to systematize the full range of PAD goals in an appropriate way. The existing approaches only cover a small scope of these.

Purpose of the meta level for PAD goals

By the differentiation of strategic goals and design goals (related to product architecture design), designers shall be supported to recognize implications of product architecture. It is supposed that in this way, first, they will understand the relevance of product architecture design by considering it in the context of the company's strategy. Second, they will be able to set different implications of product architecture into relation, for instance, when comparing modular product concepts with integral ones. This hypothesis is of central importance within the framework as it provides the basis for the evaluation of the appropriateness of further knowledge elements like PA representations, or PAD principles. Thus, Hypothesis 3 will be postulated as follows:

> **Hypothesis 3: "Design goals for product architecture design"**
> Design goals convey superordinate strategic goals of the company to the tactical vehicle of designing. The representation and assessment of relations between strategic goals and design goals for product architecture design (PAD goals) increase the overall awareness of implications of product architecture design.

Within the analysis of existing methodical approaches in Sec. 5.4, known design goals for product architecture design will be identified and classified regarding their contribution to superordinate strategic goals. On that basis a goal model can be elaborated providing an overview of strategic goals allowing access to allocated design goals.

4.2.4 Hypothesis 4: Principles for product architecture design

A central basis for product design is the product knowledge available. Thus, knowledge describing validated relations between how a product architecture can be designed and how design goals are affected are an essential element within product architecture design. This knowledge can be formalized and provided by principles. Therefore, RQ-2.3 asks for an approach to provide those principles for the design process, see Sec. 3.5.2: "*How can designers be supported accessing and combining product knowledge as principles for product architecture design?*"

Access to principles for product architecture design

In Sec. 2.2.4 knowledge was defined as a basis of decision making, illustrated, for example, in the C-K theory where concepts (C) only arise due to the combination of existing knowledge elements (K) [HW03:5]. Within design processes, this knowledge is *implicitly* available within the experience of individual persons or *explicitly* formalized as principles (also referred to as design patterns, guidelines, rules etc.) [Vaj01:1]. Therefore, principles are provided within many methodical approaches, often systematized regarding specific design goals (e.g., *Design for X*-approaches), or regarding the considered product models (e.g., principles for variation of function structures or working structures).

For product architecture design, a broad array of approaches exists describing how product architectures shall be designed, see Sec. 2.6. However, the way of how this knowledge is formalized and provided differs widely. In some methodical approaches it is described, for instance, *how* a modular architecture can be achieved, but it is not explicated *why*, i.e., which goals are addressed, e.g. [Sto97:108ff.]. Other approaches describe *why* to modularize a product by providing goals of product architecture design without describing precisely *how* to implement the modular design within a product, e.g. [Eri98:65ff.]. Moreover, approaches are mostly focusing only on the determination of structures of specific product models (e.g., function structures or building structures) or specific goals (e.g., Design for Flexibility, Lightweight, Variety etc.), see Sec. 2.6.1. Therefore, a need arises to systematize the existing knowledge, regarding the related product models, see Hypothesis 1, and the addressed design goals, see Hypothesis 3.

Chap. 3 substantiates this assumed need by highlighting a lack of knowledge for enhancing the ease in deciding on the most suitable product architectures. As a key influence factor, the availability of decision support, for instance, in the form of principles, has been identified, see factor S1. Moreover, relations to the recognition of implication of the product architecture, see factor G2, and to the appropriateness of the definition of product models, see factor S2, were shown. Therefore, the formulation of this hypothesis provides a basis for a systematization of principles for product architecture design allowing an appropriate identification, access, and application within specific design situations.

Systematizing principles for product architecture design

The solution approach within this thesis aims at systematizing principles against the background of two perspectives: First, the diverse and fuzzy described knowledge on product architecture design shall be described on a standardized basis to be able to compare it. Second, the form of systematization must allow an access to the knowledge within specific design situations. In literature, various approaches are known, addressing these aspects. On the one hand, Weber and Husung [WH16:102ff.] and Gero [Ger90:29ff.] provide systematic approaches to describe principles in a comparable form, for instance, by defining the integrated view on characteristics *and* properties as the key aspect to provide design knowledge, see Sec. 2.2.4. On the other hand, authors like Gaag [Gaa10:34], Bischof [Bis10:83ff.], and Inkermann [Ink16:77ff.] develop approaches to provide principles by an access logic defining access criteria like design goals and product models, see Sec. 2.2.4. These approaches provide a basis for the provision of principles for product architecture design. Therefore, it is differentiated between more general *basic PAD principles* and *specific PAD principles*, as proposed by Inkermann:

- **Basic principles for product architecture design** (basic PAD principles) describe general variation operations of the product architecture to be applied within PA representations. Thereby, basic principles can include as well the determination of structures within product models (e.g., integration and separation) as well as commonality across product assortments (e.g., standardization and variation).
- Specific **principles for product architecture design** (PAD principles) describe specific instances of basic principles including the description of variation operation in order to address specific goals. Specific PAD principles can include information and examples within specific fields of applications, for instance, considering specific manufacturing technologies as enablers for product architecture design.

In literature, various approaches exist that provide concepts to systematize PAD principles. For instance, Kipp [Kip12:95ff.] provides principles with references to the product models of requirements, functions, working principles, and components. However, this approach is limited to the consideration of reducing variety within product families. Approaches like Bonvoisin et al. [BHB+16:502ff.] collect principles for modularization and systematize these regarding the addressed design goals, but without the realization within different product models. Similarly, other authors (e.g., [Bau16:153ff.] [Zie12:230ff.] [Sal07:221ff.] [Ehr09:502], and [PD99:201]) provide principles focusing on specific product models or design goals. However, the challenge is to define a structure of basic PAD principles that allows to systematize all different kinds of principles.

Purpose of meta level for PAD principles

By gathering and describing the existing principles in a standardized structure within the framework for product architecture design, it is supposed to allow designers to apply existing knowledge more comprehensively. Only by an overview of various options within one collection of principles, designers will be able to identify those approaches most suitable and combine them. Thereby, the access to principles will mainly depend on an appropriate definition of PA representations as well as PAD goals. Thus, Hypothesis 4 will provide a fourth premise for the framework for product architecture design:

> **Hypothesis 4: “Principles for product architecture design”**
> For the analysis and synthesis of the product architecture, many patterns describing relations between specific designs (e.g., integral or modular product architectures) and affected design goals (e.g., weight reduction or reducing internal variety) are known providing various existing methodical approaches. The provision of this existing product knowledge as principles for product architecture design within a collection of basic principles (PAD principles) increases the accessibility and combinability of existing knowledge about the product architecture.

The basis for the elaboration of a principles’ collection is provided by the structured formalization of knowledge within existing methodical approaches. The analysis of these regarding overarching basic PAD principles as well as the derivation of extended PAD principles within the described framework will be part of Sec. 5.5.

4.2.5 Hypothesis 5: Methods for product architecture design

According to the provision of product knowledge supported by the fourth hypothesis, the fifth hypothesis aims at the purposeful proposition of procedural knowledge. Therefore, RQ-2.5 will be answered, see Sec. 3.5.2: "*How can designers be supported accessing and combining procedural knowledge as methods for product architecture design?*"

Access to methods for product architecture design

Design methods are used to carry out specific passages of a design process efficiently since the required activities can be performed based on reoccurring patterns, see Sec. 2.2.5. These patterns can be described as design methods that can be learned and applied by designers. Various of these design methods are described in literature that, in many cases, can hardly be overviewed by designers. However, design situations vary a lot and depending on factors like the defined design goals, the available information about the product represented as product models, and the phase within the design process different methods can be appropriate. Only a comprehensive understanding of the variety of existing methods can allow designers to select and apply the design methods most appropriate.

Likewise, various methods exist for product architecture design, see Sec. 2.7. Often, these methods are described independently from each other, and only few method collections exist, for instance, covering methods for integration, modularization, and platform development, see Fig. 2.18. Therefore, Otto et al. [OHS+16:1] describe the situation as follows: "The transfer of these methods, algorithms, and techniques to industrial practice is now inhibited by the seemingly broad array of material without a coherent organizing structure to compare development process tasks and the associated available methods and tools. In the design research community, each method has typically been developed independently of other methods, and it is not clear if and how various methods could be used jointly." Therefore, the access to methods and its combination is prohibited by a missing overarching framework for a description of methods according to the needs of designers.

The needs identified in Chap. 3 provide evidence to this as many factors correspond to the integration of procedural knowledge. Thus, it has been shown that the method competencies play a central role for a successful method application. However, the competencies are often limited to very few methods since a lack of an overarching structure for its description reduces the ease of learning new methods, see factor D1. Moreover, the continuity of the consideration of the product architecture is often restricted since different methods used within different phases of the development process do not correlate in its steps and created outputs, see factor E3. To address these factors, a way shall be identified to systematize methods for product architecture design that includes a clear matching of existing methods with characteristics of design situations, for instance, the defined design goals.

Systematizing methods for product architecture design

The solution approach of this thesis is based on existing approaches within design research focusing on the provision and training of design methods. For instance, Zier et al. [ZBB12:1215] aim at "cleaning up" the world of design methods by proposing to describe methods by so-called "elementary methods". Those elementary methods describe reoccurring abstract activities within methods for that specific methods provide instances concretizing the procedure for specific situations and providing additional supporting means. Similar approaches were also followed by Franke [Fra76:66ff.] and Pahl et al. [PBF+07:58ff.] describing general operation within designing, or Wulf [Wul02:61], Lindemann [Lin09:46] and Nowack [Now97:64] describing micro-cycles of design procedures. The micro-cycle of Daenzer and Huber [DH99:96] has been described in Sec. 2.2.5 with further details. It includes a flexible aggregation of general operations (clarification of goals, gathering of information, analysis, synthesis, etc.) that allows to describe the procedure within various kinds of design activities. In this way, an overarching structure for describing methods is provided as a kind of a basic method that can be specified for specific design situation. Such a structure can contribute, first, towards an easier access and combinability of methods since the description of different methods can be based on the same general operations. Second, it can contribute towards increasing the ease of learning for acquiring new method competencies. Therefore, for the systematization of methods for product architecture design, an overarching *Basic PAD Method* (similar to the micro-cycle of Daenzer and Huber) is differentiated from *specific PAD methods* (as they will be analyzed in Sec. 5.6):

- A **basic method for product architecture design** (Basic PAD Method) describes an generic procedure for carrying out activities of product architecture design. The activities occur in various design situations whereas the extent of its consideration as well as the order of the activities can be varied depending on the specific case.
- Specific **methods for product architecture design** (PAD methods) describe instances of the *Basic PAD Method* including specific descriptions of procedures and supporting means to be applied in specific design situations. Specific PAD methods often focus on the consideration of specific situations, for instance, defined by goals (a method for reducing component variety) or applied product models (a method to be applied on function structures).

In literature only a few approaches exist that compare and combine methods for product architecture design by describing overarching activities. Krause and Gebhardt [KG18:130ff.] provide one of these examples by describing an overarching procedure for the application of methods for modularization, see Sec. 2.7.3. Moreover, Bonvoisin et al. [BHB+16:496] and Erixon [Eri98:65] provide concepts for describing design methods by including various solution approaches (as principles) and various goals (as module drivers) within overarching procedures. However, each of these approaches has a specific focus. An approach covering all kinds of PAD methods does not exist in literature.

Purpose of meta level for PAD methods

The systematization of PAD methods based on a *Basic PAD Method* allows to provide a general understanding of procedures reoccurring in product architecture design. A planning of activities in accordance with the *Basic PAD Method* ensures to address the design task comprehensively, whereas the single activities of the *Basic PAD Method* can be defined by choosing and applying existing specific PAD methods. Thus, Hypothesis 5 supplements the methodical concept for the support to be elaborated by the prescriptive procedural constituent:

> **Hypothesis 5: "Methods for product architecture design"**
> Methods for product architecture design contain knowledge about how to proceed within designing by proposed procedures of activities and tools to be applied. The normalization and provision of methods based on a basic method of product architecture design (PAD methods) increase the accessibility and combinability of methods for product architecture design.

Therefore, this section provided an overview of the idea to formulate a basic method for product architecture design. In Sec. 5.6, a proposal for such a basic method will be derived from existing methods to allow a systematization of specific methods and supporting tools.

4.3 Composition within the methodical concept

The hypotheses described in the preceding section postulated approaches to improve product architecture design separately from the perspectives of the five sub-phenomena defined in Sec. 4.1.2. This section aims at illustrating the composition of these different strains in order to provide the overall structure for the framework including the support of all sub-phenomena.

Within the previous section, the five hypotheses were derived based on an overarching argumentation structure: Generally, the approaches existing in literature comprise various specific elements to support designers (e.g., specific PA representations, specific PAD stages, etc.). These elements will be called *knowledge elements* in the following. However, the common challenge regarding all five sub-phenomena is that an overarching structure is missing that allows designers to overview and access the knowledge elements required. Therefore, the hypotheses have been formulated as five approaches to introduce *meta elements* that systematize the knowledge elements on abstract respectively generic levels. Designers shall be supported by the meta elements to access those knowledge elements required within specific design situations, see Fig. 4.5.

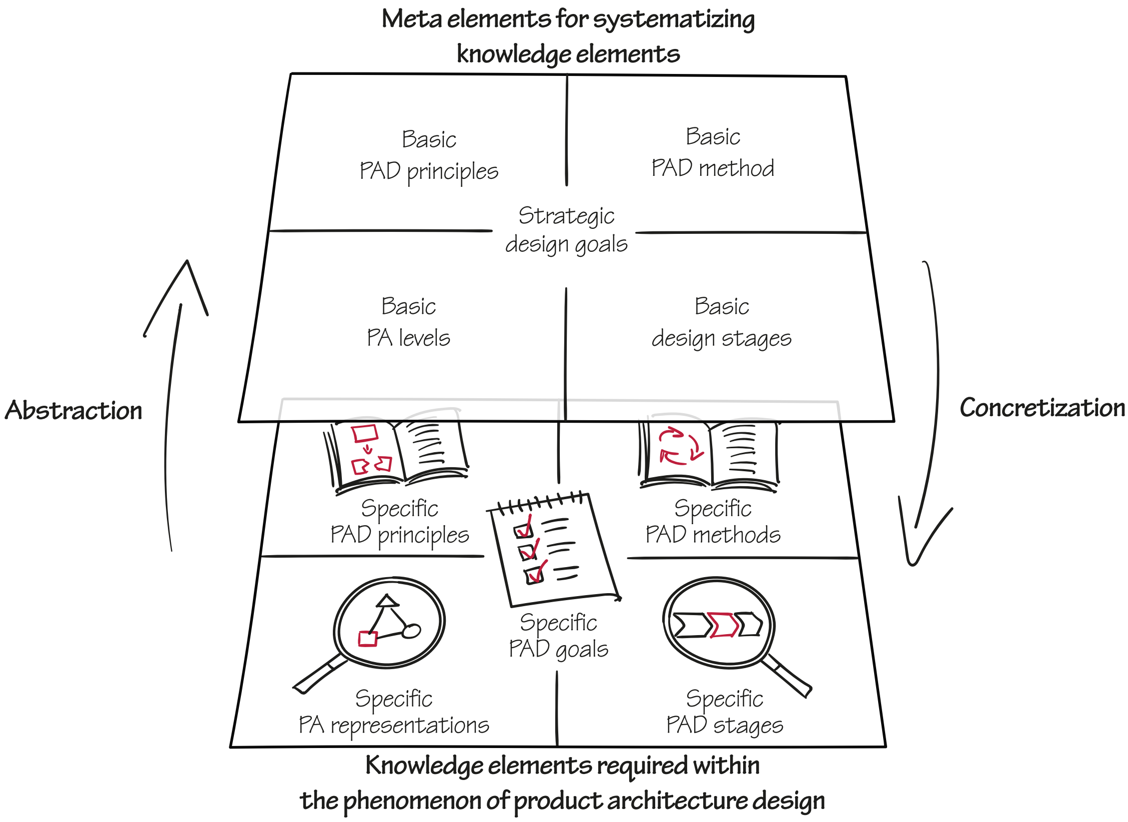


Figure 4.5: The framework comprising five meta elements to systematize specific knowledge elements required within the phenomenon of product architecture design

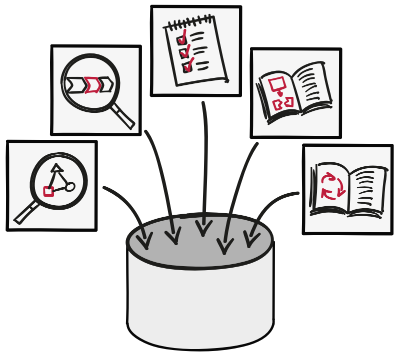
The framework elaborated within this thesis aims at interlinking these perspectives on product architecture design: First, it includes all five sub-phenomena. Second, it allows to combine specific knowledge elements on a meta level. In this way, the framework stands out in comparison to the existing approaches since these often only include support for single sub-phenomena and have a focus on specific knowledge (for instance, regarding specific goals), but do not include a meta level. Alternatively, using a metaphor of O'Donovan et al. [OEC+05:72]: A sandbox has been created that allows to build sandcastles in it. The sandbox is delineated by the five sub-phenomena and the differentiation between the meta level and the knowledge elements. The sandcastles will be placed in it when existing approaches are analyzed and classified within the framework what is the purpose of Chap. 5. Compared to other approaches, this “sandbox” claims to allow for the systematization of a huge range of approaches. In order to enable designers to identify and apply the sandcastles most appropriate for their design tasks, applicable tools including an access logic have to be elaborated. This will be in focus of Chap. 6.

4.4 Conclusion

The purpose of this chapter was to elaborate a methodical concept for the support of product architecture design. Based on the five research questions formulated in the preceding chapter, a phenomenon model to describe product architecture with five sub-phenomena was introduced. For each of these sub-phenomena, an approach was developed on how designers can be enabled to access knowledge supporting product architecture design. By this, five hypotheses were formulated providing tentative answers to the five research questions.

The key insight gained within the formulation of the hypotheses is that the success of product architecture design depends mainly on the appropriate consideration, understanding and application of five elements: PA representations, PAD stages, PAD goals, PAD principles, and PAD methods. Each of these elements contributes towards the success of the phenomenon of product architecture design whereas often the required knowledge cannot be accessed by the designers. Therefore, the hypotheses propose to elaborate overarching structures for systematizing required knowledge elements. In this way, the definition of a meta level was elaborated that defines an abstract viewpoint on the concrete PAD approaches existing in literature. By relating this meta level with the knowledge existing, a framework will be created allowing designers to access and apply those approaches most appropriate for their specific design tasks.

In the subsequent chapters, the five hypotheses will be substantiated by their implementation into a design support. For this, in a first step, each hypothesis provides a basis for the classification of existing knowledge included in PAD approaches. Therefore, Chap. 5 will conduct a structured analysis of existing approaches in order to refine the methodical concept and integrate instances of the five elements into the outlined framework.



5

Knowledge classification

Systematization of methodical approaches

The preceding chapter proposed to consider product architecture design from the perspectives of five sub-phenomena. For each of these sub-phenomena, designers can be supported by methodical approaches. However, a consistent description and overview of this knowledge is missing. Therefore, the objective of this chapter is to analyze the existing approaches and decompose the relevant knowledge regarding the five sub-phenomena. Thereby, the hypotheses formulated in the preceding chapter provide the basis for deriving overarching meta structures for each sub-phenomenon to systematize the knowledge. Since the analysis of literature will be carried out for each sub-phenomenon separately, the chapter is structured as shown in Sec. 5.1.2.

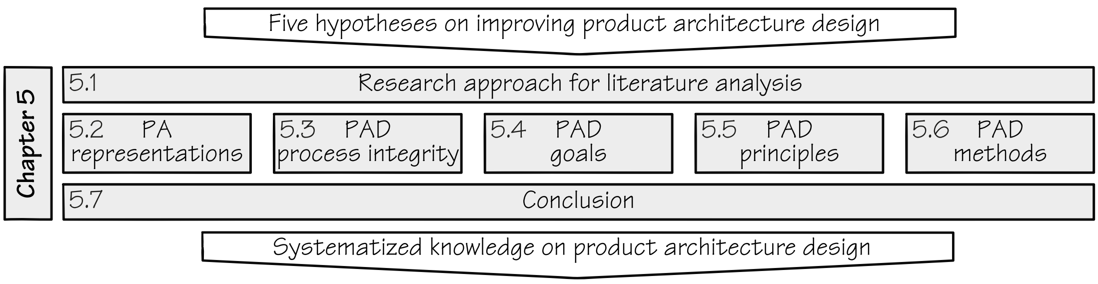


Figure 5.1: Structure of this chapter

Sec. 5.1 will outline the research approach of the analysis. Subsequently, the analysis will be described following the structure of the five hypotheses in Sec. 5.2 to 5.6. Finally, the chapter will be concluded in Sec. 5.7.

The result of this chapter is a classified overview of existing PAD approaches according to the five sub-phenomena. Regarding each sub-phenomenon, it is shown how the knowledge can be provided in a standardized form to designers. The basis for this provides a software demonstrator. The knowledge systematized will be used as a central elements within the framework that will be introduced in Chap. 6.

5.1 Research approach of literature analysis

Whereas Chap. 2 has given a broad overview of the state of the art related to product architecture design, this chapter aims at a structured analysis regarding the methodical concept elaborated in the preceding chapter. The research approach of the analysis will be described in this section starting with outlining the objective of the analysis regarding the five hypotheses in Sec. 5.1.1. Subsequently, Sec. 5.1.2 will describe the structure of the analysis, before Sec. 5.1.3 will give an overview of the PAD approaches selected for the analysis.

5.1.1 Objective of analysis

Chap. 4 has highlighted the fact that various PAD approaches exist, whereas an overarching structure to overview and combine these approaches is lacking. This was identified as a key bottleneck within design research discouraging the full exploitation of potentials of the existing research. The five hypotheses provided approaches for enhancing product architecture design by imposing a systematization on the basis of five meta structures onto existing approaches. In this way, the knowledge "stored" within the approaches shall be made accessible for designers within specific design situations.

Following this idea, this chapter aims at analyzing existing approaches in order to define specific meta structures providing the basis for classifying knowledge elements from the existing approaches. Thereby, the following five questions have to be answered according to the five hypotheses:

- Hypothesis 1: How can PA representations be classified within a structure of levels describing product models of different concretization?
- Hypothesis 2: How can integration points of PAD be classified on the basis of a general understanding of design processes?
- Hypothesis 3: How can PAD goals be classified according to strategic design goals?
- Hypothesis 4: How can PAD principles be classified according to basic PAD principles?
- Hypothesis 5: How can PAD methods be classified according to activities of a *Basic PAD Method*?

In this chapter it is neither possible to outline all analyzed approaches nor to present all extracted knowledge elements. Instead, the main target is to provide an idea of what a range of knowledge elements is existing and to show how it can be systematized. The full scope of knowledge elements will be included in a software tool. The structure for storing the knowledge elements within the tool will be described in this sections, whereas the description of the use of the tool will be described in Sec. 6.4.

5.1.2 Structure of the analysis

The structure of the analysis is performed separately for each hypothesis. However, as described in Sec. 2.1, the description of the approaches as presented in literature does not correspond to these perspectives. Therefore, each approach is screened respecting the included knowledge regarding the hypotheses. For this, the following three questions are answered for extracting the relevant knowledge:

1. Do the approaches themselves include a **meta structure for systematizing and accessing the knowledge** (see also "access logic" in Fig. 2.6)?
2. How can the knowledge elements included in the approaches be **classified according to an overarching meta structure** derived by answering the preceding question?
3. What is a suitable structure for **providing the knowledge elements** to designers within an overarching framework (supported by a software tool)?

Accordingly, the following five sections will be divided in three parts addressing the three questions separately.

5.1.3 Selection of approaches for analysis

The approaches analyzed in this chapter have been identified by various search methods in online literature databases and cross-references in established literature. The approaches are related to the topics connected with product architecture design as described in Chap. 2. Thereby, the focus was not exclusively on obvious keywords like "product architecture" or "product architecture design" but also on related goals (e.g., "lightweight design", "flexibility", or "upgradeability") or established terms for classes of approaches (e.g., "function integration", "modularization", or "platform design"). Obviously, the here presented selection of approaches is not complete since the number of existing approaches in literature is very great due to the different focuses. Nevertheless, in the authors' view, the most cited approaches in established literature are included within the analysis what allows the conclusion that further approaches can be included in further works.

An overview of the analyzed approaches is shown in Tab. D.1 in Appendix D. Therein, for each approach the relevance regarding the five hypotheses is shown. It can be seen that most approaches do not contribute to each hypothesis to the same extent. Few approaches, for instance from Ulrich and Eppinger [UE12:189ff.], Ziebart [Zie12:154ff.], Wie [Wie02:114ff.], Bauer [Bau16:109ff.], Firchau [Fir03:40ff.], and, particularly, the approaches included in the *Integrated PKT Approach* of Krause and Gebhardt [KG18:208ff.] (Halfmann [Hal14:81ff.], Blees [Ble11:65ff.], Kipp [Kip12:73ff.]), see Sec. 2.7.3, contribute to all hypothesis. Many approaches, for instance, only focus on the provision of PAD representations or PAD principles. Furthermore, the rating scheme of the approaches elucidates whether the approaches provide a meta structure of the included knowledge (see first question in preceding subsection) or only include one or more knowledge elements in an unstructured way (see second question).

In the following sections, a small selection of these approaches will be cited as examples of the analysis. However, many approaches will not be mentioned explicitly in this chapter due to a limitation of space. Nevertheless, the knowledge elements of the approaches are included in the knowledge base of the tool and can be found as an extract in Appendix E.1 to E.4.

5.2 Classification of PA representations according to Hypothesis 1

The product architecture can be represented in different ways. The aim of the literature analysis that will be conducted in this section is to understand the purpose of different PA representations and to define an overarching structure to allow designers to generate the most suitable representations within specific design situations. Therefore, Sec. 5.2.1 aims at the elaboration of an overarching structure for PA representations in form of basic PA levels. On that basis, a classification of existing approaches from literature will be carried out whose results will be outlined in Sec. 5.2.2. Finally, it will be demonstrated how PA representations can be provided to designers to be used during designing in Sec. 5.2.3.

5.2.1 The meta structure for PA representations: basic PA levels

Within Sec. 2.3 it has been pointed out that various product models representing the product architecture – PA representations – are proposed to be used supporting analysis and synthesis. However, the purposes of the application of the different PA representations differ widely depending on the information that is included in the representations. Thus, in Sec. 2.3.1, it has been shown that three different aspects of the product architecture are included: the *structure* of a product, the *allocations* between different product models, and the *commonality* within a product assortment. Furthermore, it has been shown that the concretization of the information about the product varies depending on the stage within the design process or the suitably for making specific decisions, see Sec. 2.3.2. For instance, Kipp [Kip12] illustrates this within the *Variety Allocation Model* that describes the product architecture in the level of required product properties, function structures, working principles, and components, see Fig. 2.13. Similarly, other authors describe the variety of product models to be used for determining the product architecture comprehensively, see [BHB+16, Deu15, Fir03, OHS+16, Wie02, Zie12].

In order to structure this variety of PA representations, Hypothesis 1 proposes to generate a meta structure of *basic PA levels* that allow to classify the existing PA representations, see Sec. 4.2.1. The purpose of the definition of basic PA levels is to allow designers to understand the full scope of what information about the product *can possibly* be included in a PA representation. On that basis, designers shall be enabled to define PA representations appropriate for specific design tasks. The premises on the definition of the PA levels can be described from two perspectives: First, the levels need to be suitable for the description of PA representations applied within the existing PAD approaches, and therefore, be suitable to address specific design goals, see Sec. 5.4. Second, the levels need to be defined in accordance to product models generally applied within design processes in order to allow designers to understand and adapt the meta structure to individual situations, see Sec. 5.3.

Following these two premises, five general PA levels have been identified as suitable for describing product architectures. The levels are distinguished by the degree of concretization of the included product characteristics, see Tab. 5.1. For each level, the table comprises a definition regarding the product characteristics described, examples of properties that can be assessed within the level, and literature referring to such a level.

On the whole, the defined levels are in accordance to product models described in established design literature, see Sec. 2.2.1. For instance, Birkhofer describes function structure (functions), effect structure (effects), working structure (working bodies), and building structure (components) analogically to the first four levels [Bir11]. Similarly, other approaches comprise these levels [Ehr85, Lin09, PBF+07, RFS71, Rot00, Rud98, Suh98]. The fifth level – the module structure – is rarely explicitly referred to in established literature. Nonetheless, many approaches include a definition of modules, for instance, for establishing a structure for design process organization (e.g., [VDI18, VDI93]), for variety management (e.g., [VDI04]), or manufacturing (e.g., [Sau06]).

The definition of these levels provide a suitable basis for describing PA representations as it allows to include all three dimensions of the product architecture within one generic model, compare Fig. 2.9. Fig. 5.2 gives an illustration for this. Therefore, *structure*

Table 5.1: General definition of the five basic PA levels

Level	Characteristics	Examp. Properties	Literature
Function structure	The function structure consists of sub-functions and their interactions. It describes the teleology of the product, i.e., what it is for.	reliability, applicable use cases, complexity in terms of funct. coupling	[EGB11] [GK04] [Rot00] [Suh98] [VDI93] [PBF+07]
Effect structure	The effect structure describes physical, chemical, biological etc. effects and their interactions. It describes how to fulfill the required sub-functions.	realizable outputs and their value ranges, noise, warming	[RFS71] [Rot00] [Kol98] [HE88] [PBF+07] [AHC15]
Working structure	The working structure consists of working bodies and their interactions on working surfaces. It describes how to realize the required effects.	adaptability, rigidity, kinematics	[RFS71] [Rot00] [VDI93] [PBF+07]
Building structure	The building structure describes the embodiment of technical elements as components and their interactions as interfaces. It describes the product's geometry as it is manufactured.	size, robustness, manufacture costs	[RFS71] [Rot00] [Suh98] [VDI93] [PBF+07]
Module structure	The module structure describes physical and/or organizational aggregation of components as modules and their interactions. It describes the product passing through different product life phases (development, distribution, repair, etc.).	configurability, repairability, upgradeability	[Ble11] [Sau06] [VDI93] [Cae91]

is described as the interactions of design units within one level within one product. *Allocations* are described as vertical relations between design units of different levels. *Commonality* is described by horizontal associations between design units of different products. A specific PA representation comprises the description of a defined scope of design units (functions, effects, working bodies, components, or modules) within one or more levels. For instance, the *Product Architecture Scheme* after Ulrich (compare Fig. 2.10) describes design units within the level of the function structure (functions) and within the level of the module structure (modules). Depending on the purpose of the application of the PA representation, several of the dimensions described before can be included.

The classification of PA representations described in literature according to these levels shall allow to differentiate between different viewpoints on the product architecture. The results of the analysis of examples of PA representations will be described in the

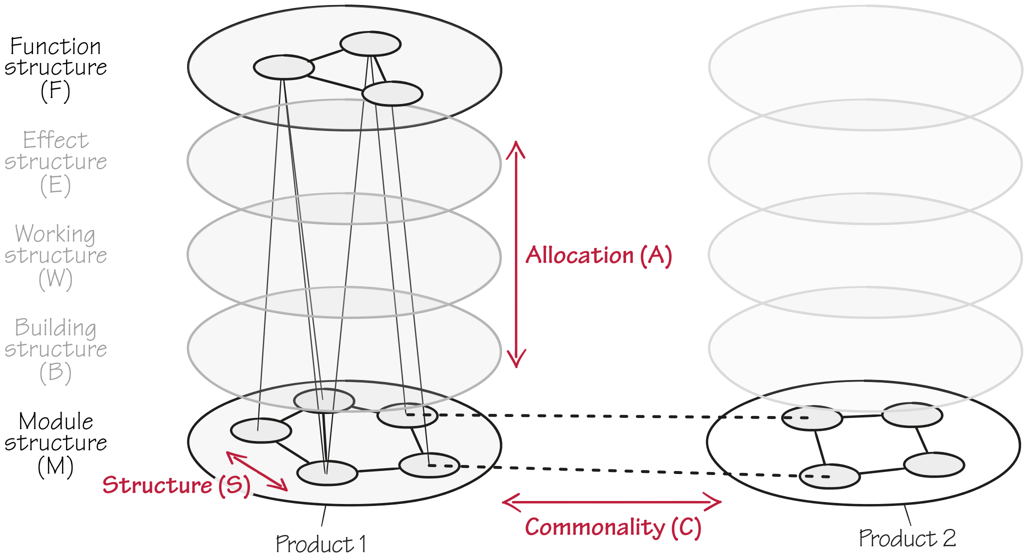


Figure 5.2: Meta structure for describing PA representations on five basic levels on the dimensions of structure, assortment, and commonality

subsequent subsection.

5.2.2 Analysis of existing approaches

For the analysis of PA representations, the criteria of the meta level before described were applied for classification. Obviously, further criteria, for instance, the addressed design goals, the applied design principles, the related methods, etc. can be applied. However, in focus of this section is the validation of the meta structure allowing to describe which *characteristics* of the product are included in a PA representation. Thus, Tab. 5.2 shows the classification of examples of PA representations regarding the included PA levels (F, E, W, B, and M). Within the cells of the matrix, for each correlation, it is specified which aspect of PA representation (see Sec. 2.3.1) is represented: the *structure* between design units within a level (S), the *allocations* of design units of another level (A), and the *commonality* within the product assortment (C).

The extract of the analysis represented in the table shows that the PA representations comprise the whole classification space by addressing all five levels while representing structure, allocations, and commonality. In order to illustrate the method of analysis, three examples shall be described that have already been introduced in Fig. 2.10 in Sec. 2.3.2: The *Geometric (Working) Structure* of Roth [Rot00], the *Product Architecture Scheme* of Ulrich [Ulr95], and the *Variants Tree* of Caesar [Cae91].

Thus, the *Geometric (Working) Structure* is allocated to the level of the working structure. The PA representation includes working bodies and working surface pairs. Therefore,

Table 5.2: Examples of PA representations classified according to the basic PA levels and the included dimensions of PA representation

PA representation	**Literature**	**PA levels**				
		F	**E**	**W**	**B**	**M**
Geometric (Working) Structure	[Rot00:237ff.]	-	-	S	-	-
Variants Tree	[Cae91:48ff.]	-	-	-	S/C	-
Product Architecture Scheme	[Ulr95:420ff.]	A	-	-	A	S
Flow-oriented Function Structure	[Sto97:46ff.]	S	-	-	-	S
Solution-function Matrix	[KG03:217ff.]	-	S	-	-	-
Architecture Graph Representation	[Bau16:156ff.]	-	-	-	S/C	S
Modular Products Systematics	[PBF+07:496ff.]	A	-	-	-	S/C
Variety Allocation Model[7]	[Kip12:73ff.]	C/A	-	C/A	C/A	-
Module Interface Graph[7]	[Ble11:75ff.]	S	-	-	S/C	S
Module Process Chart[7]	[Ble11:65ff.]	-	-	-	A	S
Generic Organ Diagram	[Har06:100ff.]	S/C	-	-	-	S
METUS Diamond	[FGG+13:256ff.]	A	-	-	A	S

Legend: S $\widehat{=}$ structure, A $\widehat{=}$ allocations, C $\widehat{=}$ commonality

the PA representation shows the structure of the product without including dimensions of allocations or commonality. The *Product Architecture Scheme* in contrast does not describe the structures of design units within levels. Instead, it represents the allocations between functions (function structure) and components (building structure). Thereby, the representations support the identification of modules, although these are not explicitly included in the representation. However, the allocations of functions to components shall allow designers to analyze interactions between modules in order to decouple them. The last representation, the *Variants Tree* puts the focus on the representation of commonality of components. Therefore, the assembly structure of components is illustrated whereas variants of components are explicitly highlighted.

In summary, the systematization of PA representations according to the PA levels as well as the three dimensions of PA representation is suitable for providing an overview of the different approaches. Therefore, decisions on the most suitable PA representation can be based on this classification what will be demonstrated in the following subsections focusing on the way of providing knowledge about PA representations to designers.

[7] Approach is part of the *Integrated PKT Approach*, see Sec. 2.7.3 and [KG18:208ff.]. The parts are listed separately to distinguish between the different PA representations used within the parts.

5.2.3 Provision of knowledge about PA representations

The provision of PA representations to designers shall allow them to capture the most important information to decide on the suitability of the representation for a specific design task. Therefore, for each representation, a *representation card* is proposed to be elaborated. Supported by a software tool, designers can choose a representation card from a filterable list of representations. An example of such a card is shown in Fig. 5.3. It describes the *Geometric Working Structure* of Roth as described in Sec. 2.3.2.

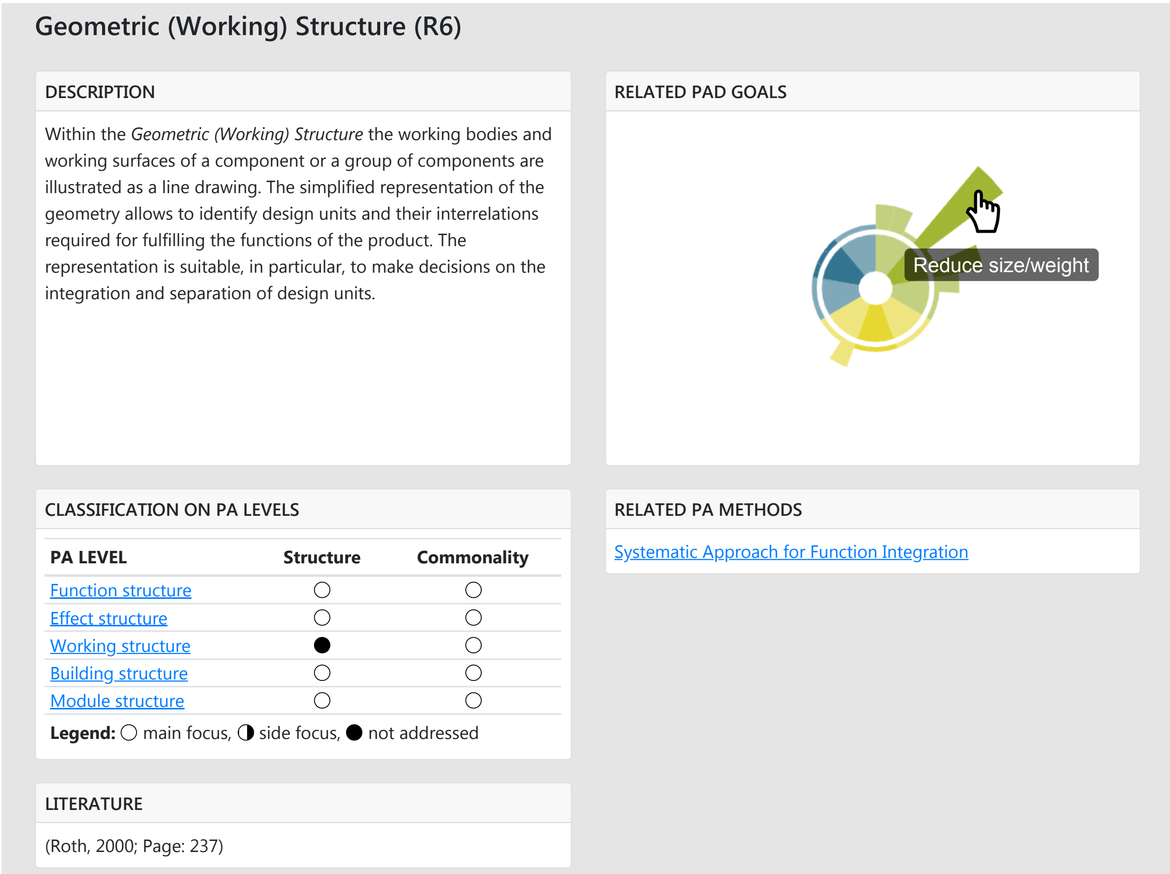


Figure 5.3: Example of a PA representation card

The elements that are included within a representation card are the following:

- the **title** and **number** (compare Appendix E.1) of the PA representation
- a brief **description** of the PA representation
- an allocation of the PA representation to **PAD goals** that can be addressed by the representation (Therefore, the allocation is visualized by a radar chart as it will be described in Sec. 6.3.1. Per hover-effect, the name of the goals can be displayed as shown on the example of *reduce size/weight*. A further description of how these correlations are determined follows in Sec. 6.4.)

- a **classification on PA levels** including the dimensions of PA representation *structure* and *commonality*
- an allocation to **PAD methods** that are based on this type of representation
- a list of related **literature**

In this way, from the representation card, it can be read out what the main idea of the representation is and how it is related to PAD goals, PA levels, and PAD methods. However, the only brief description can only provide a first understanding of the representation and cannot substitute further review of the related literature.

Overall, 19 PA representations have been identified in literature and inserted into the software tool. The complete list of the PA representations is shown in Appendix E.1. How these PA representations will be applied in design situations, will be provided by the framework introduced in Chap. 6.

5.3 Classification of process integrity of PAD according to Hypothesis 2

Product architecture design can be integrated into design processes at different points of time. The aim of the literature analysis conducted in this section is to understand the characteristics of design processes in order to ascertain a general meta structure for allocating PAD to design processes. Therefore, in Sec. 5.3.1 an overarching systematization of design processes by general design stages will be elaborated. On that basis, in Sec. 5.3.2, existing PAD approaches will be classified regarding their integration into these basic stages. Finally, in Sec. 5.3.3, it will be outlined how the knowledge about PAD stages can be provided to designers.

5.3.1 The meta structure for PAD process integrity: basic design stages

While specific instances of design processes can differ widely between design projects, companies, and branches, Sec. 2.2.2 has highlighted that, in many cases, it is appropriate to model design processes by representing the considered product models and the addressed design goals within different stages. As shown in Sec. 2.4, this modeling approach can illustrate that product architecture design can be allocated to different points of time of a design process – depending on the product models that are used as basis for addressing the goals. Accordingly, Hypothesis 2 (cf. Sec. 4.2.2) postulates that designers can be enabled to integrate PAD into design processes by modeling design processes within a formalism of basic PAD stages that can be recognized in each design process related to the determination of the product.

For the definition of basic PAD stages, the product models used within the stages play a central role. In the preceding section, five basic PA levels have been derived systematizing PA representations within existing PAD approaches. These five levels shall also provide the basis for describing design processes since all relevant activities for the analysis and synthesis of the product architecture must be related to at least one of these five levels. Accordingly, each stage of a design process considering one of these levels is a potential stage for integrating the consideration of the product architecture – a basic PAD stage. Thus, when a design process is modeled representing the allocation of each stage to these levels, designers are supported in recognizing the relevance of design stages for considering product architecture design.

Therefore, the meta structure for PAD stages is defined by the five PA levels as "determining the function structure", "determining the effect structure", etc. With examples of design processes, the following section will show how these basic PAD stages can allow designers to allocate product architecture design appropriately.

5.3.2 Analysis of existing approaches

As mentioned before, the aim of this section is not to outline an extensive overview of possible PAD stages described in literature, since these are depending strongly from the individual design context. Nevertheless, in a few examples, it shall be shown how the proposed meta structure of basic PAD stages generally allows to systematize existing approaches. In this way, the assumption that the basic PA levels will also allow allocating PAD into design processes independently from the specific contexts of the design project will be supported by evidence.

Therefore, Fig. 5.4 shows a reference process that shall be considered at this point as an example of a design context as described in generic design approaches. The process is split into two sections. The first section describes a typical procedure for a new product design, cf. [VDI93] [PBF+07] [Rot00]. The process depicts the steps starting from the "determination of functions and their structures" up to the "division into realizable modules", whereas the product is progressively concretized. Therefore, the levels are passed through from top to down. In the second section of the process, a procedure for an adaptive design is shown that aims at redesigning an already existing product, cf. [Kip12:96], compare Fig. 2.13. Starting point for this approach is a description of the components of a product. In order to generate new "better" solutions, the components are redesigned before the module structure is adapted to the new design. Optionally, while redesigning the components, further abstraction of the product can be made to develop new solutions based on variations of the working structure, effect structure, and function structure.

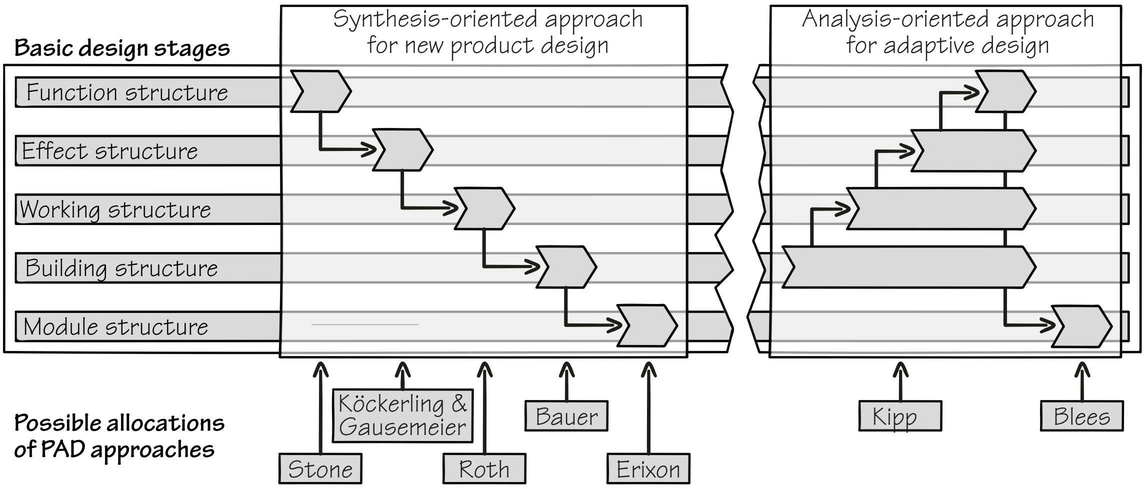


Figure 5.4: Examples for allocations of PAD approaches to reference design processes

Within the reference process, examples of PAD approaches can be allocated by their considered product models. Picking up approaches from Tab. 5.2, the approaches of Stone [Sto97], Köckerling and Gausemeier [KG03], Roth [Rot00], Bauer [Bau16], and Erixon [Eri98] can be allocated to the first section of the reference process according to the corresponding levels of the included PA representations. In the second section, generally, the same approaches can be applied again when the corresponding PA levels are considered (again). However, explicitly, the approach of Kipp [Kip12] aims at guiding designers through the redesign of a product proposing to apply PAD principles on the levels of the building structure, the working structure, and the function structure. Finally, the approach of Blees [Ble11] can be applied, to optimize the module structure of the product regarding the life phases of the product.

Obviously, the here shown PAD approaches classified by the reference process only provide examples. Alternatively or additionally, each other approach can be applied that bases on the proposed consideration of the PA level corresponding with the stages of the process. Therefore, an illustration of design processes as shown in Fig. 5.4 can support the evaluation of the appropriateness of a PAD approach for a stage. However, further criteria for deciding on PAD approaches are necessary, for instance, the PAD goals relevant to the design task.

5.3.3 Provision of knowledge about PAD stages

As described in Sec. 4.2.2, design processes are individual, and a determination of a design process including the PAD stages is always dependent of the context, for instance, defined by the relevant PAD goals, the available resources, the time constraints, the initial situation, etc. Nevertheless, the examples of PAD stages as proposed in the approaches described in the preceding subsection show that knowledge on PAD stages can be analyzed and extracted from literature. However, each of these approaches is built on own reference processes considering specific contextual factors. Therefore, an extraction of the proposals for PAD stages, must include these constraints. However, the comprehensive exposition of these constraints goes beyond the scope of this thesis.

Consequently, within this thesis, the provision of knowledge about PAD stages is limited to the conveyance of an understanding of the dependencies between the basic design stages in the form of PA levels. Therefore, the knowledge base of the framework shall include *PA level cards* that include the most important information about the PA levels that are considered as basic design stages. One example of a level card is shown in Fig. 5.5.

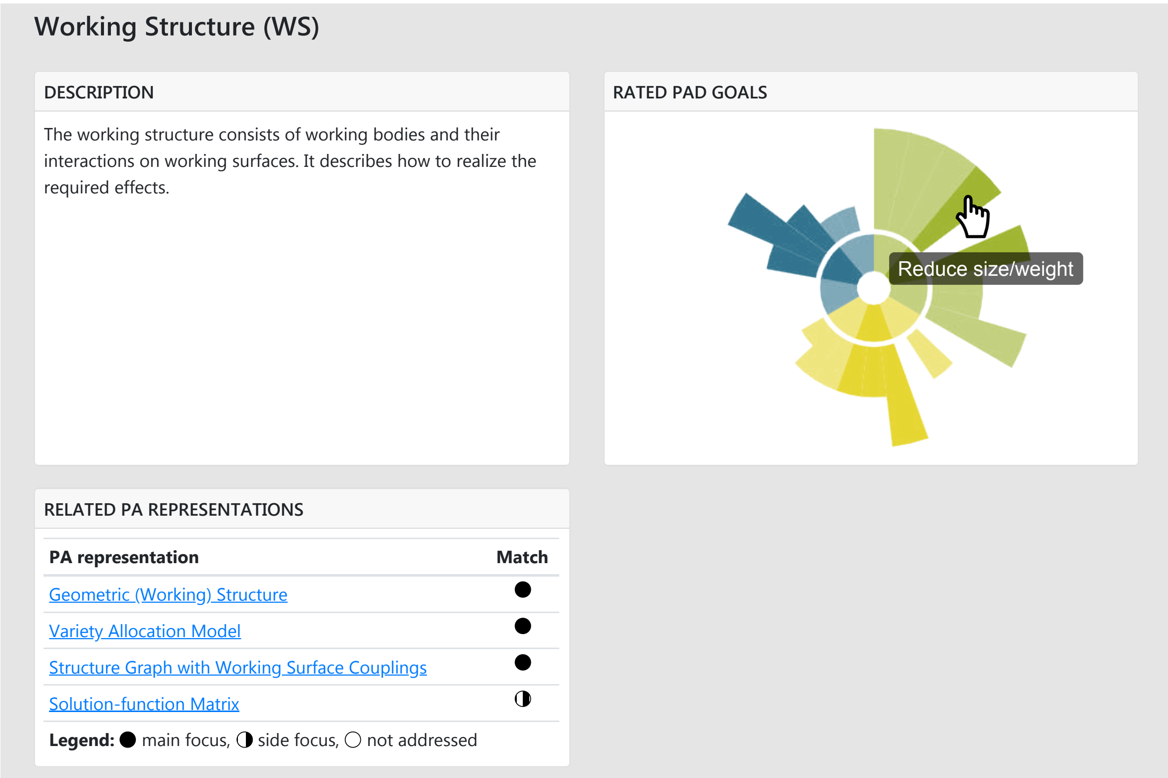


Figure 5.5: Example of a PA level card

The elements that are included within a level card are the following:

- the **title** of the PA level
- a brief **description** of the PA level (see Tab. 5.1)
- an allocation of the PA level to **PAD goals** that can be addressed by the level (Therefore, the allocation is visualized by a radar chart as it will be described in Sec. 6.3.1. Per

hover-effect, the name of the goals can be displayed as shown on the example of *reduce size/weight*. A further description of how these correlations are determined follows in Sec. 6.4.)

- an allocation of the PA level to **PA representations** that include aspects of this PA level

In this way, all five PA levels are described within the knowledge base. As most important use within the framework for product architecture design, the correlations between PAD goals and PA levels is seen. This will be further described in Sec. 6.4.3.

5.4 Classification of PAD goals according to Hypothesis 3

Reasons why product architecture shall be considered explicitly during designing are formulated in literature from different perspectives. Aim of the analysis conducted in this section is to systematize the variety of possible PAD goals. Therefore, in Sec. 5.4.1 a model of strategic goals for designing will be elaborated as a basis for understanding design goals of a company. The allocation of existing PAD approaches to these strategic goals will be demonstrated in Sec. 5.4.2 in order to provide evidence for the appropriateness of the defined strategic goals. Finally, Sec. 5.4.2 will introduce a way of providing the knowledge about PAD goals to designers.

5.4.1 The meta structure for PAD goals: strategic PAD goals

In Sec. 2.5 it has been shown that PAD approaches have a focus on a limited number of PAD goals, in most cases. Even though some approaches exist aiming at providing an overview of several design goals for designers, they are either lacking of detail (goals are described superficially) or of extent (only a few goals are included). Therefore, within Hypothesis 3 the approach was formulated to systematize the variety of PAD goals within an overarching goal model whereas the structure of this model shall be defined by strategic goals of the company. Thereby, the strategic perspective shall ensure that designers will be able to prioritize the goals from a superordinate viewpoint. In this subsection, it shall be discussed how these strategic goals can be defined in an appropriate way to cover the scope of goals for product architecture design.

Generally, different approaches exist to systematize design goals in literature. For instance, Pahl et al. propose checklists to identify relevant requirements for design projects categorized according to types of functions, domains of development, and effects on after-sales [PBF+07:149]. Similarly, Patzak focuses on technical aspects categorized according to *functionality*, *physical appearance*, and the *product's use behavior* [Pat82:33ff.]. A wider view provides the life cycle approach of Birkhofer describing the effects of product development on various life phases that require consideration in task clarification [Bir11:348ff.]. Beyond that, other approaches describe goals for product design from the business perspectives, for instance, allocating design goals to success factors like quality, time, and cost [LI14:103ff.]. A well-established approach combining various of these perspectives is described by Osterwalder [Ost04:42ff.], see also [OP10:18ff.]. He proposes a so-called *Business Model Canvas* categorizing company goals regarding their effects on the business areas *value proposition*, *customer interface*, *infrastructure management*, and *financial aspects* whereas each of the business areas is specified by goal categories, see Fig. 2.5.

For the systematization of PAD goals, it seems appropriate to choose a categorization of goals that includes the business perspective as well as the functional-technical perspective, as it is often highlighted within literature, e.g. [Deu15, Eri98, Göp98, KG18, LI14]. Therefore, in this thesis, the strategic goals are defined according to the Business Model Canvas of Osterwalder as it seems appropriate to cover aspects of the whole life cycle. By integrating the categories of product properties proposed by Patzak to specify the field *value proposition*, also functional-technical aspects are covered. This results in the strategic goals for product architecture design as described in Tab. 5.3. Therein, the business field *financial aspects* is omitted for the reason that this field is not affected directly by the product architecture. Instead, the product architecture affects the other three fields (covering all life phases) that are directly linked to incurred costs.

In order to provide evidence to the defined strategic goals, the subsequent subsection analyzes existing PAD approaches. In this way, it shall be shown that the scope of strategic goals is suitable to cover all PAD goals designated within the existing approaches.

5.4.2 Analysis of existing approaches

As described before, the range of PAD goals is wide, and a comprehensive overview of all possible goals does not exist in literature. Therefore, in this subsection, exemplary approaches are analyzed regarding their addressed goals. Most of the approaches explicitly point out their purpose by the addressed goals, for instance, by describing intended impacts on life phases (e.g., [BHB+16, Ble11, Eri98]), affected product properties (e.g., [Ren07, UE12, Zie12]), or involved departments of the company (e.g., [YW07]). In contrast, other approaches do not explicitly highlight the addressed goals only referring to objectives like “modularization” (e.g., [SWC00]) or “function integration” (e.g., [Rot00]). In that cases, the addressed goals were derived from the described context of the application of the approaches.

Table 5.3: Strategic goals for product architecture design

Business area	Strategic goal	Description
Value proposition	Functio-nality	The scope and quality of the fulfillment of the required functions (in- and output) of the product.
	Physical appearance	The visible condition in that a product appears to the customer and affects the product's use during its lifetime.
	Use behavior	The interaction of the product with its (changing) environment.
Customer interface	Customer relations	The link between customer and company that is established in order to maintain the relationship.
	Market segments	The target group a company currently or prospectively aims to reach and serve with the products and services.
	Distribution channels	The touch points of the company to communicate with and to reach customers to deliver products and services.
Infra-structure management	Partners	Voluntarily initiated cooperative agreement between companies to reproduce and create value.
	Company resources	The long-term ability of the company to execute a repeatable pattern of actions that are necessary to reproduce and create products and services.
	Activities	The arrangement of activities and resources that are necessary to reproduce and create products and services.

An excerpt of the analysis is shown in Tab. 5.4. Therein, some exemplary approaches are listed. The addressed goals identified within the approaches are allocated to the nine fields of strategic goals. A full circle indicates the strategic field as an explicitly named key objective of the approach. The circles partly filled indicate side objectives of the approaches.

From the table it can be seen that the scopes of approaches vary widely. For instance, the *Modular Function Deployment* approach of Erixon [Eri98:72ff.] comprises the evaluation of the relevance of *module drivers* for the design of components of the product. Each of the twelve module drivers refers to an implication of the product architecture, and therefore, to a possible PAD goal. For instance, the module driver *Technology Push* targets at increasing the flexibility of companies to react to technology changes what refers to the strategic goal *market segments*. Overall, the module drivers cover a scope of seven of nine strategic goals of the company mainly in the business areas *customer interface* and *infrastructure management*. In contrast, the approach for function integration of Ziebart [Zie12] mainly addresses strategic goals within the business area of *value proposition*, for instance, by increasing the amount of product functions (*functionality*) or reducing

Table 5.4: Allocation of exemplary PAD approaches to strategic goals

PAD approach	**Literature**	**Goals**								
		Functionality	**Physical appearance**	**Use behavior**	**Customer relations**	**Market segments**	**Distribution channels**	**Partners**	**Company resources**	**Activities**
Modular Function Deployment	[Eri98:72ff.]	○	○	●	●	●	◐	●	●	●
Implications of Funct. Integration	[Zie12:154ff.]	●	●	●	○	◐	○	○	●	◐
Potentials of Modularity	[KG18:105ff.]	○	○	●	●	●	●	●	●	●
Impacts of Platform Design	[Ren07:118ff.]	○	○	◐	◐	●	◐	○	●	●
Implication of PA on the Firm	[YW07:118ff.]	○	○	○	●	●	●	●	●	●
PA Assessment	[Fix05:345ff.]	○	○	○	○	○	○	●	●	●
Implications of PA	[UE12:187ff.]	●	●	●	●	●	○	○	●	●
Implications of Modularity	[NBR98:1ff.]	○	○	◐	●	○	○	○	●	◐
Theory of Modular Design	[Sto97:46ff.]	○	◐	○	○	○	○	○	●	●
Approach for Funct. Integration	[Rot00:237ff.]	○	●	○	○	○	○	○	●	○
Variety-oriented Design	[Cae91:48ff.]	○	○	○	○	●	●	○	●	●
Funct. Integration and Separation	[KG03:217ff.]	●	●	○	○	○	○	○	◐	○
Support for Design for Variety	[Kip12:73ff.]	○	○	○	○	●	●	○	●	●
Modular Product Development	[Göp98:112ff.]	○	○	◐	◐	◐	○	○	●	●
Benefits of Modularity	[GPZ03:295ff.]	○	○	◐	●	●	●	○	●	●

Legend: ● ≙ explicitly in focus, ◐ ≙ side focus, ○ ≙ not considered

weight (*physical appearance*).

Overall, the excerpt of the analysis presented in Tab. 5.4 allows to conclude that the focuses on PAD goals of PAD approaches in literature are diverse and only a few approaches cover a wider range of the strategic fields. In this context, it must be considered that the presented table only breaks down the objectives of the approaches on the level of the nine strategic goals. Each approach addresses strategic goals like *market segments* with a specific focus. The different focuses included in approaches have been analyzed in order to describe specific PAD goals. In this way, for each strategic goal, three subordinated PAD goals were defined resulting in a list of 27 PAD goals in total. Fig. 5.6 illustrates this by showing the decomposition of the strategic goal of *market segments* into three PAD goals. The above described example of *Modular Function Deployment* addresses by its module drivers two of the three assigned PAD goals: The module driver *Technology Push* addresses the PAD goal *increase reaction flexibility for market changes*. The module drivers *Styling* and *Technical Specifications* address the PAD goal *increase variety of products*.

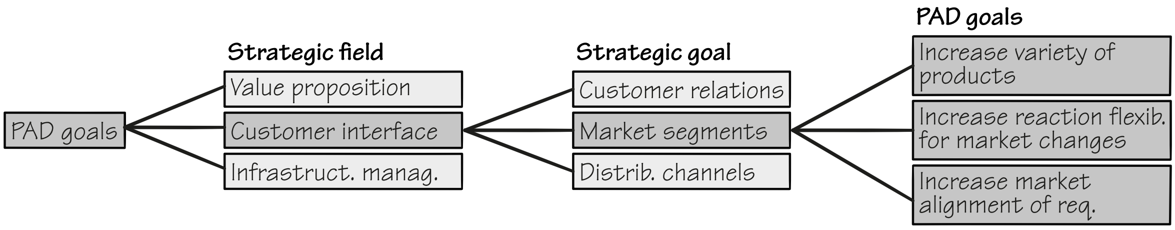


Figure 5.6: Hierarchical decomposition of goals in strategic fields, stratigic goals, and PAD goals

By the analysis of the existing PAD approaches, in this way, 27 PAD goals have been identified. By these, the diversity of the focuses becomes even more apparent. However, this level of detail of the analysis is not presented here but will be included in the software tool for knowledge provision. Additionally, a list of all 27 PAD goals is included in Appendix E.2.

5.4.3 Provision of knowledge about PAD goals

Due to the variety of existing PAD goals and the limitation of most approaches to cover only some strategic fields, the provision of knowledge about PAD goals shall be integrated into the framework for product architecture design. Within a goal chart (see Sec. 6.3.1) designers will be enabled to overview the possible goals. For each of the 27 goals, a *goal card* shall allow designers to get further information about the goal and identify PAD representations, PAD principles, and PAD methods to address the goal. An example of such a goal card is shown in Fig. 5.7.

The elements that are included within a goal card are the following:

- the **title** and **number** (compare Appendix E.2) of the PAD goals
- a brief **description** of the PAD goal
- a classification of the **PAD goal** according to the strategic goals of a company within the goal chart (as it will be introduced in Sec. 6.3.1)
- an allocation of the PAD goal to **PA levels** on that this goal can be addressed (A further description of how these correlations are determined follows in Sec. 6.4.)
- a list of related **literature**

Improve process organization (G25)

DESCRIPTION

The efficiency of communication processes within a company including development, production, and distribution. Product architecture design can affect the process organization, for instance, by contributing to a suitable breakdown structure of the product that allows teams of persons within a firm or suppliers to work on modules of the product independently of each other.

CLASSIFICATION IN GOAL CHART

RELATED PA LEVELS

PA representation	Match
Function structure	●
Effect structure	◑
Working structure	◔
Building structure	◔
Module structure	●

Legend: ● main focus, ◑ side focus, ○ not addressed

LITERATURE

(Steward, 1981; Page: 71)
(Pimmler & Eppinger, 1994; Page: 1)
(Stone, 1997; Page: 2)
(Fixson, 2005; Page: 348)
(Renner, 2007; Page: 118)
(Yassine & Wissmann, 2007; Page: 127,130)
(Kipp, 2012; Page: 76)
(Ulrich & Eppinger, 2012; Page: 191)

Figure 5.7: Example of a PAD goal card

In this way, all 27 PAD goals are described. A crucial key of the framework for product architecture design is the relations of PAD goals to the allocated PAD representations, PAD principles, and PAD methods. Only in this way, a goal-oriented design of the product architecture can be supported. How these correlations are drawn within the software tool will be further described in Sec. 6.4. However, the goal card does not show the related PAD representations, PAD principles, and PAD methods due to a possibly to large number of elements. Therefore, the goal-oriented access to the elements will be allowed by a filter function within the software tool, which will be introduced in Sec. 6.4.4.

5.5 Classification of PAD principles according to Hypothesis 4

Knowledge of how a product architecture shall be designed is existing in various forms in literature. Aim of the analysis conducted in this section is to elaborate and apply a systematization of the available knowledge in form of PAD principles. Therefore, in Sec. 5.5.1, a structure of basic PAD principles will be elaborated providing the foundation for classifying specific PAD principles in Sec. 5.5.2. In Sec. 5.5.3, principle cards will be introduced as means for providing knowledge about PAD principles to designers.

5.5.1 The meta structure for PAD principles: basic PAD principles

Principles comprise the knowledge required for the analysis and synthesis of products, see Sec. 2.2.4. For product architecture design, various principles are included within existing approaches. However, a comprehensive overview of the existing knowledge is lacking, see Sec. 2.6. Therefore, Hypothesis 4 postulates that a systematization of principles within a structure of overarching basic principles can allow easier access and combinability. This can provide the basis for an improved support for designers in specific design situations, see Sec. 4.2.4.

In order to discuss the question of an appropriate classification of principles, it shall be reflected what a principle's description must include to be applied during designing based on the CPP approach after Weber, see Sec. 2.2.4. First, it must include the description of specific patterns to determine *product characteristics*, and second, the implications of these patterns on *product properties* respectively the design goals. Thus, a systematization of principles can be made according to both characteristics and design goals. A structure for accessing PAD principles on the basis of PAD goals has been elaborated in the preceding section. At this point, the focus shall be put on the arrangement of characteristics – thus, how PAD representations can be synthesized in order to fulfill PAD goals. For this reason, the classification of PAD principles can be based on the classification of PAD representations, see Sec. 5.2, i.e., on the concepts of basic PA representations (function structure, effect structure, etc.) and the three dimensions of product architecture (structure, allocations, and commonality).

Considering this definition of PA representations, PAD principles must comprise the knowledge about how variations of these structures affect design goals. This can be examined by considering the three dimensions of PA representations separately, see also Sec. 2.6.2: Regarding the first dimension *structures of design units*, the product can be changed by *integrating* and *separating* design units, whereby these variations are made within one of the five defined levels of concretization (e.g., by integrating functions, integrating effects, integrating working bodies, etc.). In literature those principles are also described as consolidation, aggregation, or conjunctions (alternative to integration) respectively differentiation, partitioning, or segregation (alternative to separation). Regarding the second dimension *commonalities between design units*, changes within the product architecture can be made by *standardizing* design units (making two units common) and *varying* design units (making two units distinctive). These operations can be carried out on all five PA levels (e.g., by standardizing functions, standardizing effects, standardizing working bodies, etc.). Accordingly, the four types of basic PA principles can be differentiated as shown in Fig. 5.8.

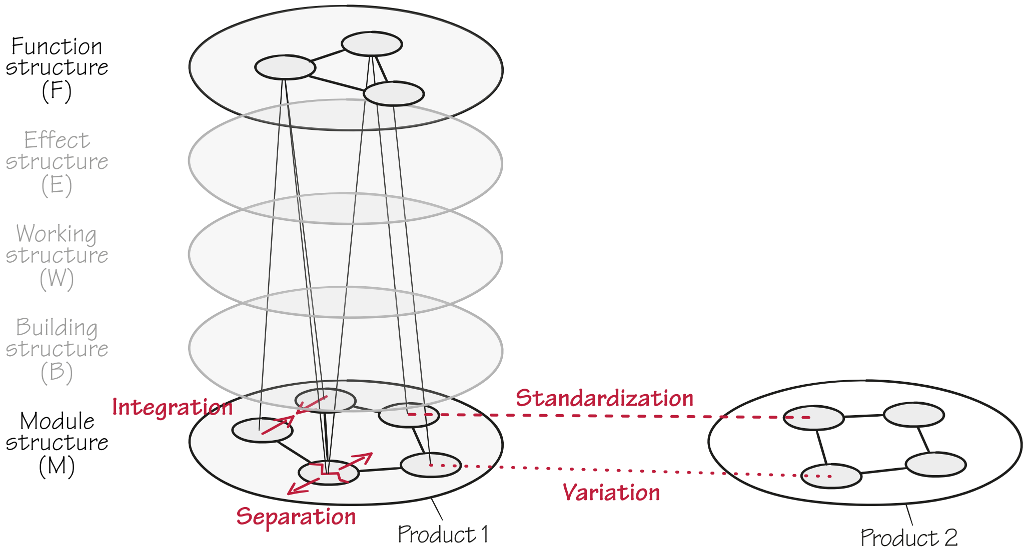


Figure 5.8: Illustration of the basic PAD principles, compare Fig. 5.2

The third dimension *allocations between design units of different PA levels* does not reveal new basic PAD principles that can be demarcated clearly from those defined before. Even though in literature patterns are described regarding this dimensions like one-to-one mapping (cf., [Sal07]), or modularization (cf., [Ulr95]), the principles behind the application of this patterns are based on variations within the first and second dimension. The reason for this results from the fact that statements on allocations between design units of different concretization are made by designers to understand the product better, but cannot be synthesized *directly*. For instance, an allocation of a function to a component can be analyzed and considered during synthesis. However, to change an allocation (e.g., allocate a function to another component), functions and/or components have to be redefined. Figurative speaking, a vertical line within Fig. 5.8 cannot be redrawn without considering the horizontal dimensions to change design units before. In contrast to this, statements on the structure relations (first dimension) and commonality relations (second dimension) between design units are formulated within one PA level (horizontal lines within Fig. 5.8). To carry out an integration, for instance, two separate components are integrated within the dimension of the *structure of design units*. Thus, the integration can be applied "directly" whereas, as a side effect, also the vertical relations have been changed.

Therefore, the four basic PAD principles are described as *integration*, *separation*, *standardization*, and *variation*. Each of them can be carried out within all of the five levels of PAD. In this way, they provide also a means to achieve changes within the third dimension. An overview of the four basic PAD principles is given in Tab. 5.5. It is described how a principle can support the analysis and synthesis of a product concept.

Table 5.5: Overview of the four basic PAD principles

Basic principle	Analysis	Synthesis
Integration	Identification of design units within one product with potential to be integrated	Creation of *one* new design unit integrating the purposes of the original design units
Separation	Identification of design units within one product with potential to be separated	Redefinition of the design unit to be split up in *two* (or more) separate design units fulfilling the purpose of the original design unit
Standardization	Identification of variant design units of different products with potential to be standardized	Harmonization/assimilation of characteristics of variant design units to create one standardized design unit
Variation	Identification of (standardized) design units of different products with potential to be differentiated	Variation of characteristics of design units to create two different design units

The basic PAD principles as defined here only provide a generic description of the activities to be carried out by designers. To apply these principles, descriptions on the design goals affected by the application and guidelines for inducing the desired state of the product need to be supplemented. Therefore, specific PAD principles need to be formulated. However, the basic PAD principles as well as the PA levels as defined in this section are not consistently used in literature. Therefore, an analysis of existing approaches needs to be carried out as described in the following subsection in order to derive specific PAD principles.

5.5.2 Analysis of existing approaches

In order to identify specific PAD principles in literature, existing PAD approaches have to be analyzed regarding statements on patters for arranging the product architecture *and* on the effects on design goals. Those statements can be found formulated explicitly in the form of principles (e.g., [Bau16, BHB+16, KK08]) or implicitly within textual descriptions of methods, guidelines, or best-practices (e.g., [KG03, PBF+07, Ste81]). In each case, the aim of the analysis is to extract the essential knowledge and reformulate it in a consistent way.

An extract of the principles analysis is shown in Tab. 5.6. The selection of these few principles from the countless range of principles existing in literature shall highlight the analysis method. Therefore, on the one hand, principles from the *Design for Variety* approach of Kipp [Kip12:72ff.] have been chosen for illustration. The approach contains twelve principles that can be applied subsequently on different levels of concretization, see Fig. 2.13. The allocation of the principles shows that they consider the basic PAD principles *integration*, *separation*, and *standardization*. However, at first sight, this cannot be recognized from titles. For instance, the principle “elimination of technical variety” describes an approach to analyze for components that are similar within a product family, but not the same. The principle aims at *standardizing* these components in order to reduce the variety of components being handled by the company. Similarly, for all other principles of Kipp clear allocations to one of the basic PAD principles can be identified.

Table 5.6: Allocation of exemplary PAD approaches to strategic goals

PAD principle	Literature	PA level	Basic principles			
			Integr.	Sep.	Stand.	Var.
elimination of technical variety of components	[Kip12:98]	B	○	○	●	○
differentiation of unsuitable variant components	[Kip12:98]	B	○	●	○	○
oversizing of unsuitable variant components	[Kip12:102]	B	○	○	●	○
integration of variant components	[Kip12:102]	B	●	○	○	○
substit. var. working princ. by var. working elem.	[Kip12:106]	W	○	○	●	○
shifting of physical variety to software	[Kip12:107]	W	○	●	○	○
reducing or simplifying variant working elements	[Kip12:108]	W	●	○	○	○
postpone variation along the flow	[Kip12:113]	F	○	○	●	○
standardization of variant inputs	[Kip12:113]	F	○	○	●	○
minimizing coupling betw. variant branches of flows	[Kip12:114]	F	○	●	○	○
modularize regarding carry-over	[Eri98:72]	M	○	●	○	○
modularize regarding technological evolution	[Eri98:72]	M	○	●	○	○
modularize regarding technical specifications	[Eri98:72]	M	○	●	○	○
achieve variants by cut-to-fit modularity	[PD99:201]	B	○	○	○	●
achieve variants by mix modularity	[PD99:201]	B	○	○	○	●
exploit existing capabilities	[Zie12:36]	E	●	○	○	○
expanding solution space by components variation	[Zie12:38]	W	●	○	○	○
integration by overcoming component partitions	[Zie12:45]	B	●	○	○	○

Legend: ● ≙ explicitly in focus, ◐ ≙ side focus, ○ ≙ not considered

On the other hand, further principles are included in the table proposed by Erixon [Eri98:72ff.], Pine and Davis [PD99:201ff.], and Ziebart [Zie12:35ff.]. In contrast to the principles of Kipp, each of these approaches focuses on one kind of principles: Erixon on modularization, Pine and Davis on variation, and Ziebart on integration. Also on these principles applies that the titles often do not clearly convey the approach of the principles.

In summary, the results of the analysis provide evidence for the assumption of the possibility of systematizing PAD principles regarding the categories described in Sec. 5.5.1. However, in this subsection, the examples described can not show the full range of existing principles. Moreover, it can be recognized simply by regarding the titles of the principles that the kind of provision of the principles is far inconsistent. Therefore, the way of providing the principles shall be adapted to a standard what will be described in the following subsection.

5.5.3 Provision of knowledge about PAD principles

The provision of PAD principles shall allow designers to capture most relevant information about principles to be able to apply them. The before described way of providing knowledge about PAD goals in the form of *goal cards* has shown a means for the identification of PAD principles. Thus, when selecting a specific PAD goal, designers are allowed to access PAD principles that shall be represented as *principle cards*. An example of a principle card is shown in Fig. 5.9 describing the derived principle *separate design units by differentiating standard and variant sections*. This principle is also included in Tab. 5.6 as *differentiation of unsuitable variant components* based on [Kip12:98ff.] and [KK08:430]. From the original descriptions of the principle, it can be deduced that one possibility to overcome *unsuitable variant components* is to separate their standard and variant sections. The principle card describes this in a general way.

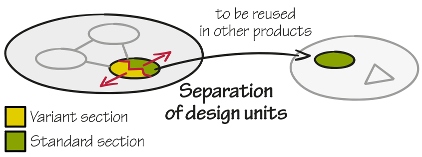
As mentioned before, the way of existing PAD principles in literature is inconsistent. Therefore, the principle cards describe them in a standardized way including following elements:

- the **title** of the PAD principle that is in each case formulated according to the scheme "[basic principle] design units [key idea of the principle]" and **number** (compare Appendix E.3)
- a brief **description** of the PAD principle with an illustration according to the scheme of Fig. 5.8
- an allocation to **PAD goals** that can be addressed by the principle (A further description of how these correlations are determined follows in Sec. 6.4.)
- an allocation to **PA levels** that provide a basis for the application of the principle
- an allocation to **PAD methods** that support the application of the principle
- an illustrative **example** of the principles application

Separate design units by differentiating standard and variant sections (P25)

DESCRIPTION

The separability of standard and variant sections allows reusing the standard sections in other products of the product family or product assortment. Therefore, a separation of design units provides the basis for increasing the ratio of standard parts within a company.



AFFECTED GOALS

PA LEVELS FOR APPLICATION

PA LEVEL	Structure	Commonality
Function structure	○	○
Effect structure	○	○
Working structure	○	●
Building structure	○	◑
Module structure	○	○

Legend: ○ main focus, ◑ side focus, ● not addressed

RELATED PA METHODS

Method of Variety-oriented Product Design
Integrated PKT-Approach for Developing Modular Product Families

EXAMPLE

Lenses of cameras (e.g., DSLRs) are used in many cases with an UV filter attached onto the lens. Technically, the UV filter can be integrated into the lenses within the lens assembly. However, in order to allow for individually choose the kind of UV filter or replace it by other filters, the application of the principle is appropriate by separating the UV filter from the lens assembly.

LITERATURE

(Kipp & Krause, 2008; Page: 430)
(Kipp, 2012; Page: 98)

Figure 5.9: Example of a PAD principle card

- a list of related **literature**

In this way, the principle card should allow to consider principles from different literature sources in a fast way. However, the description of the principles is still limited to a manageable extent. Less experienced designers must possibly acquire more information about the principle in referenced literature.

Overall, 57 principles have been identified. A tabular overview of the principles are included in Appendix E.3.

5.6 Classification of PAD methods according to Hypothesis 5

PAD approaches comprise in many cases procedural knowledge regarding designing activities in the form of methods. Aim of this section is to decompose established procedures in order to elaborate an overarching procedure for PAD – the *Basic PAD*

Method. Therefore, in Sec. 5.6.1 the activities of the *Basic PAD Method* will be predefined based on other generic design approaches. According to this, existing PAD approaches will be analyzed to identify their contributions towards the activities of the *Basic PAD Method* in Sec. 5.6.2. Finally, Sec. 5.6.3 will outline an approach to provide knowledge about PAD methods to designers.

5.6.1 The meta structure for PAD methods: *Basic PAD Method*

Methods are operable patterns of activities within a design process, see Sec. 2.2.5. For product architecture design, various methods exist that are described, for instance, by procedures of activities in which different tools are applied, see Sec. 2.7. However, for designers without much experience in applying methods, it is hard to overview, select, and combine the available methods. Therefore, Hypothesis 5 postulates to elaborate a meta structure of methods' activities in order to systematize and access the available knowledge within existing approaches, see Sec. 4.2.5.

For the systematization of PAD methods, the basic assumption is that reoccurring patterns can be identified within existing approaches. These patterns shall be named as "basic PAD activities" (according to "elementary design methods" after Zier et al. [ZBB12]). These basic PAD activities – once understood – shall allow designers to apply different PAD approaches easier and enable them to combine single activities (and tools) of different approaches, for instance, by combining activities supporting analysis and synthesis of one approach with activities supporting evaluation of another approach. Moreover, the procedure of the basic PAD activities shall allow to be run through iteratively allowing cascading of several approaches, cf. [Wul02:61].

As described in Sec. 4.2.5, several approaches exist in literature that describe generic approaches for designing, also referred to as micro-cycles of designing. Regarding a suitability for describing PAD approaches, it shall be reflected about relevant elements used within design activities as described within the hypotheses. Therefore, Hypothesis 3 emphasized the importance of the clarification of goals. Hypothesis 1 highlighted the variety of representations of product models that can be generated. Hypothesis 4 described PAD principles supporting the analysis and synthesis of product architectures. Comparing these activities with general approaches for designing, all of these activities are included in many of these, see, for instance, [Dör87, Loh13, MGP60, Now97, Pat82, PBF+07, Rop75, Wul02]. Especially, the *Systems Engineering Problem-Solving Approach* of Daenzer and Huber [DH99:96] draws many parallels, compare Fig. 2.8. Therefore, the *Basic PAD Method* shall be described by a set of general activities. Tab. 5.1 gives an overview of the defined activities with their general purpose and examples regarding an adoption to product architecture design.

Table 5.7: Basic PAD activities within the *Basic PAD Method*

Step	Description	Example
Defining PAD goals	Clarification of relevant PAD goals for the specific design situation.	Rating the relevance of PAD goals like reducing weight, increasing adaptability, and offering a high product variety.
Generating PA representations	Derivation of a product model representing relevant aspects of the PA.	Generation of a working structure representing the relations between working bodies.
Analyzing/ Synthesizing the PA	Carrying out variations of the PA in order to fulfill design goals.	Application of integration principles to working bodies in order to reduce weight.
Evaluating the PA	Interpreting the achieved new state of the product and decide on further steps.	Evaluation whether the elaborated concepts represent a satisfying result and considering to iterate.

The order in that the basic PAD activities are listed in Tab. 5.7 represents a standard sequence as proposed by most approaches. However, depending on the specific design task, the order can be varied. For instance, the procedure can start with the step of *generating PA representations* when the information situation about the product does not allow to define PAD goals, cf. [VDI04:27ff.]. Then, an initial PA representation can be *evaluated* (skipping the *analysis and synthesis of the PA*), to be able to make statements on a desired state of the product architecture in the form of PAD goals.

These examples show that the basic PAD activities can be arranged depending on the needs of the designers. However, the general description of the activities – as the *Basic PAD Method* – shall allow to highlight the activities most important for successful product architecture design and provide a basis to specify the procedure by the combination of specific PAD methods supporting single activities. These shall be classified in the *Basic PAD Method* in the following subsection.

5.6.2 Analysis of existing approaches

To allocate specific knowledge about PAD to the activities of the *Basic PAD Method*, existing PAD approaches need to be analyzed by a classification of the procedural knowledge included. Therefore, each PAD approach including a specific PAD method (in most cases, described as a procedure of several steps) is analyzed regarding the coverage of the four activities of the *Basic PAD Method*. An extract of the result of this analysis is shown in Tab. 5.8. The full circles indicate a strong focus of the approaches to support the basic activity; the partly filled circles indicate a limited support provided, for instance, if the activity is mentioned, but not supported in detail.

Table 5.8: Allocation of exemplary PAD approaches to PAD methods

PAD approach	**Literature**	**Activities of the *Basic PAD Method***			
		Clarifying PAD goals	**Generating PA representations**	**Analyzing/ Synthesizing the PA**	**Evaluating PA concepts**
Modular Function Deployment	[Eri98:72ff.]	●	◐	◐	●
Systematic Approach for Function Integr.	[Rot00:245]	○	●	●	○
Method of Module Heuristics	[Sto97:46ff.]	○	●	●	○
Modular Product Development	[PBF+07:499ff.]	◐	●	●	◐
Dev. of Change-robust Platform Archit.	[Bau16:109ff.]	●	●	●	○
Generic Approach of Modularization	[KG18:130ff.]	◐	●	●	○
Function-oriented Platform Development	[Ren07:100ff.]	●	◐	◐	◐
Function Integration and Separation	[KG03:217ff.]	○	●	●	○
Method of Variety-oriented Product Design[8]	[Kip12:73ff.]	◐	●	●	●
Method for Dev. Modular Product Families[8]	[Ble11:65ff.]	●	●	◐	●
Change Mode & Effect Analysis	[RVC+03:2ff.]	○	◐	◐	●
Product Family Master Plan	[Har06:81ff.]	○	●	◐	●

Legend: ● ≙ explicitly in focus, ◐ ≙ side focus, ○ ≙ not considered

The given examples illustrate the diversity of the focuses of the existing approaches. However, it can clearly be seen that especially the *generation of PA representations* as well as the *analysis and synthesis of the PA* is supported by most approaches to some extent while the two remaining activities are not addressed, in many cases. However, for each activity approaches exist that provide a comprehensive support.

To illustrate the mode of analysis, *Modular Function Deployment* after Erixon [Eri98] shall be explained in more detail. The approach lays the focus on the formulation of module drivers that represent possible PAD goals regarding a modularization of the product addressing different life phases. Therefore, the approach mainly addressed the *clarification of PAD goals* by providing an overview of possible PAD goals and a method

[8] Approach is part of the *Integrated PKT Approach*, see Sec. 2.7.3 and [KG18:208ff.]. The parts are listed separately since they include independently used methods with steps with different focus.

for rating their relevance for specific sub-functions (within the *Module Indication Matrix*). Moreover, for each module driver methods for the *evaluation of the PA* are given. However, for the *generation of PA representations* (sub-functions within the *Module Indication Matrix*) or the realization of the aspired modularization within *analysis and synthesis of the PA*, only few support is given. Instead, the concept generation is explicitly left up to a "creativity phase" of the designers [Eri98:82].

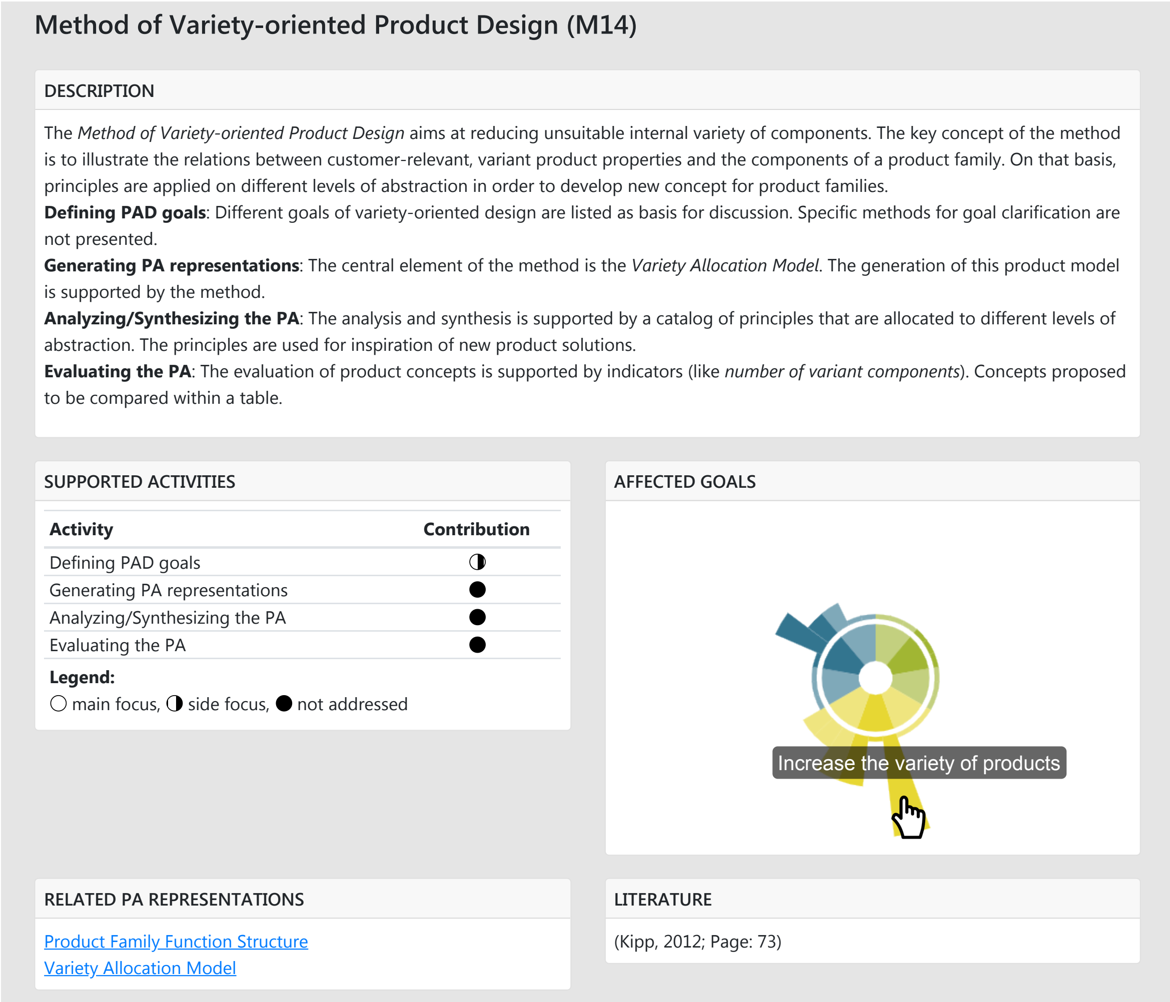
In contrast, other approaches like the *Method of Module Heuristics* after Stone [Sto97] or the *Systematic Approach for Function Integration* after Roth [Rot00] do not explicitly support the activities *clarification of PAD goals* and *evaluation of the PA*. Instead, the focus lies on the *generation of PA representations* in the form of a *Flow-oriented Function Structure* respectively a *Geometric (Working) Structure* and the *analysis and synthesis of the PA* by providing PAD principles (*heuristics* respectively *generic possibilities for function integration*).

In summary, the analysis provides evidence to the hypothesis by approving the applicability of the meta structure of the basic PAD method to classify procedural knowledge of existing PAD approaches. However, the results presented show that approaches provide support for at least one basic PAD activity, but only in a few cases for all. The classification shall allow designers to understand this weakness of single approaches and allow them to combine several methods in order to receive a comprehensive approach. Therefore, the required knowledge must be provided to designers in an appropriate way what will be considered in the following subsection.

5.6.3 Provision knowledge about of PAD methods

The preceding section has shown that knowledge about PAD methods exists in PAD approaches. However, in many cases, not all activities of the basic PAD method are covered. Furthermore, the single PAD approaches, obviously, put the focus on a specific purpose when proposing a PAD method. Therefore, it is required for designers to access and combine specific PAD methods according to the design task considered. Therefore, a collection of specific PAD methods is required that can provide relevant information to designers to evaluate the suitability of the support. Obviously, a brief description of the method can not substitute the consultation of the original source to understand and apply the method. Therefore, a *method card* as illustrated on an example in Fig. 5.10 can only give a brief overview of the method.

The elements that are included within a representation card are the following:



Method of Variety-oriented Product Design (M14)

DESCRIPTION

The *Method of Variety-oriented Product Design* aims at reducing unsuitable internal variety of components. The key concept of the method is to illustrate the relations between customer-relevant, variant product properties and the components of a product family. On that basis, principles are applied on different levels of abstraction in order to develop new concept for product families.
Defining PAD goals: Different goals of variety-oriented design are listed as basis for discussion. Specific methods for goal clarification are not presented.
Generating PA representations: The central element of the method is the *Variety Allocation Model*. The generation of this product model is supported by the method.
Analyzing/Synthesizing the PA: The analysis and synthesis is supported by a catalog of principles that are allocated to different levels of abstraction. The principles are used for inspiration of new product solutions.
Evaluating the PA: The evaluation of product concepts is supported by indicators (like *number of variant components*). Concepts proposed to be compared within a table.

SUPPORTED ACTIVITIES

Activity	Contribution
Defining PAD goals	◑
Generating PA representations	●
Analyzing/Synthesizing the PA	●
Evaluating the PA	●

Legend:
○ main focus, ◑ side focus, ● not addressed

AFFECTED GOALS

RELATED PA REPRESENTATIONS

Product Family Function Structure
Variety Allocation Model

LITERATURE

(Kipp, 2012; Page: 73)

Figure 5.10: Example of a PAD method card

- the **title** of the PAD method that is in each case formulated including the denomination of the corresponding activity of the basic PAD method and **number** (compare Appendix E.4)
- a brief general **description** of the PAD method supplemented by specific description of how the four activities of the basic PAD method are supported
- an allocation to **PAD goals** that are intended to be addressed by the method
- an allocation to the **activities** of the basic PAD method that are supported by the method
- an allocation to **PAD representations** that provide a basis for the application of the method
- a list of related **literature**

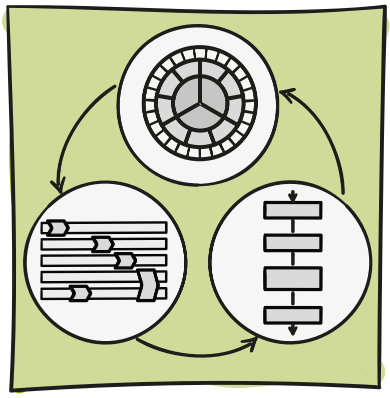
Overall, 19 PAD methods have been identified in literature that are prepared as method cards. An overview of these methods is provided in Appendix E.4.

5.7 Conclusion

The aim of this chapter was to systematize existing knowledge of PAD approaches. While Chap. 2 has only presented a broad overview of the state of the art, this chapter carried out a classification following the structure proposed by the five hypotheses formulated in Chap. 4. Therefore, for each hypothesis, a meta structure was elaborated providing the basis for the classification of knowledge elements from literature. Finally, for PAD representations, PAD goals, PAD principles, and PAD methods a standardized means was proposed to provide the included knowledge to designers in the form of profile cards that are provided by a software tool. In this way, for each hypothesis, a structured overview of knowledge elements has been elaborated, whereas in this chapter only exemplary extracts of the full analysis could be presented.

This chapter provided evidence for the five hypotheses in respect to the fact that PAD knowledge can be classified on meta structures (basic PA levels, basic PAD stages, strategic goals, basic principles and, activities of the basic PAD method). Furthermore, the classification of knowledge elements allowed to obtain an overview of the extent and variety of existing approaches. In this way, the need for an overarching framework for product architecture design was underlined. This framework can facilitate the access to the knowledge that might be combined within specific design situations.

What this chapter could not provide is an appropriate access structure for the knowledge elements. Even though the single results regarding the five hypotheses defined the systematization of the knowledge, a comprehensive approach to be applied during design practice was not considered. This will be the main objective of Chap. 6: To elaborate a framework that allows accessing the systematized knowledge elements of all five hypothesis in specific design situations.



6

Solution approach

A framework for product architecture design

In the preceding chapters, two key insights have been gained: First, the phenomenon of product architecture design can be differentiated by five sub-phenomena according to the five fields of design research, see Chap. 4. Second, the variety of knowledge elements existing in literature can be classified within a meta structure, see Chap. 5. However, to facilitate the provision of existing knowledge, a methodical support needs to be elaborated that can be easily understood and applied by designers. This framework shall allow designers to access the knowledge when required in a design process. Addressing these needs, the objective of this chapter is to transfer the intermediate results of the previous chapters into a framework that allows designers to benefit from the systematized knowledge within different scenarios of designing. The basis for this will be provided by the five sub-phenomena that will be merged into three operational constituents. Therefore, within the structure of this chapter, the description of the constituents plays a central role, see Fig. 6.1.

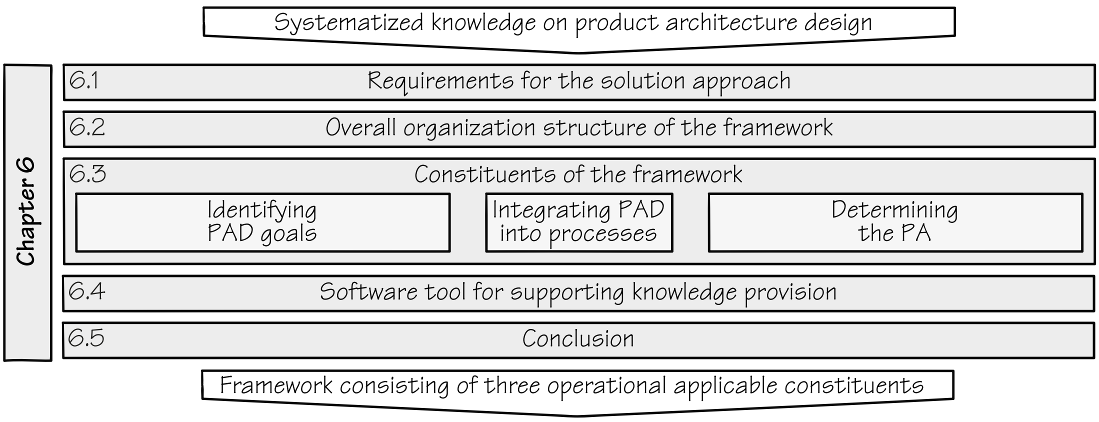


Figure 6.1: Structure of this chapter

In order to derive the necessity and delineation of the three constituents, in Sec. 6.1, the intent of the framework will be clarified. Subsequently, in Sec. 6.2, the framework's overall concept will be outlined. Sec. 6.3 will illustrate the constituents in detail allowing for access and application of the knowledge elements elaborated within the preceding chapter. Finally, in Sec. 6.4, the software tool (as referenced within the preceding chapter to include profile files of PA representations, PAD stages, PAD goals, PAD principles, and PAD methods) will be introduced as a means for the provision of the knowledge elements. The chapter will be concluded in Sec. 6.5.

The result of this chapter is a general description of the framework's constituents and provided support by the software tool. The application of the framework will be part of the initial validation in Chap. 7.

6.1 Clarification of the intent of the framework

According to Blessing and Chakrabarti the aim of the *Prescriptive Study I* is to document the intended design support [BC09:141f.]. This documentation shall include a description of the support's quality and how it works, as well as an intended plan for its introduction into design practice. Within this section, a brief overview of the intent of the framework's introduction is provided. Therefore, in Sec. 6.1.1 the added value will be highlighted with respect to existing approaches of product architecture design. Subsequently, Sec. 6.1.2 will specify the scope and intended impact of the framework. In Sec. 6.1.3, the context of the framework's application will be depicted including the description of the users. Finally, the intended plan for implementation will be outlined in Sec. 6.1.4.

6.1.1 Added value with respect to existing approaches

At this point, it shall be highlighted again that the framework developed in this thesis does not claim to replace one or many of the PAD approaches existing in literature. Rather, the needs identified in Chap. 3 have shown that it is required to provide a support that allows to recognize, identify, and apply the existing approaches appropriately. Therefore, the key objective of the framework for product architecture design is to provide such an overarching approach – a framework – that allows to implement existing approaches appropriately.

To give a more illustrative picture of the intended support, the metaphor of a sandbox for a framework of O'Donovan et al. [OEC+05:72] has already been introduced in Sec. 4.3. According to that, the framework shall allow designers to build sandcastles.

In this case, a sandcastle is a PAD approach that is appropriate for a specific design situation. Obviously, many PAD approaches exist that are built according to specific blueprints for a limited scope. Within the preceding chapter, these blueprints have been analyzed and decomposed in order to derive the key concepts of the approaches: the knowledge elements. The framework aims at allowing designers to access these knowledge elements and enable them to build their own sandcastle. Therefore, PA representations, PAD stages, PAD goals, PAD principles, and PAD methods are the most relevant knowledge elements that need to be included in a specific PAD approach.

Consequently, the added value of the framework is not to expose completely new knowledge concerning product architecture design. Instead, the value for designers, as well as researchers, is to allow them to access the knowledge elements in an appropriate way. Thereby, they are enabled to create their own PAD approach customized for a specific design situation on the basis of the generic blueprints of the here proposed framework.

6.1.2 Scope and intended impact

The focus of the existing PAD approaches varies widely as shown in the preceding chapter. In order to define the scope of the framework, a limitation of the addressed issues has to be made. The foundation for this is provided by the phenomenon model elaborated in Sec. 4.1.2 that dissects product architecture design into five sub-phenomena. These sub-phenomena have been defined on the basis of the needs identified in literature and design practice according to the improvement of product architecture design. The hypotheses postulated in Sec. 4.2 provided approaches for *basic elements* which shall be supported these sub-phenomena. Accordingly, the scope of framework covers the following situations in designing:

- defining appropriate *PA representations* on the basis of *basic PA levels* (see Hypothesis 1)
- integrating PAD into design processes by allocating it to *PAD stages* on the basis of an overarching understanding of design processes provided by *basic design stages* (see Hypothesis 2)
- identifying and prioritizing *PAD goals* on the basis of *strategic goals* of a company (see Hypothesis 3)
- determining the PA by accessing *PAD principles* on the basis of *basic PAD principles* (see Hypothesis 4)
- determining procedures for PAD by accessing *PAD methods* on the basis of *activities of a Basic PAD Method* (see Hypothesis 5)

By supporting these five sub-phenomena, a positive impact of the framework on the success of product architecture design is assumed. Therefore, the framework lays the focus on five of in total twelve identified influence factors. By this limitation, other activities will not be supported directly, compare Tab. 3.3. For instance, it has been identified that the *scope of system consideration* (I1) or the *designers' mindset* (E2) represent other issues impeding the success of product architecture design. Even if these issues are not directly addressed by the five hypotheses, they are closely linked to the five situations described above. Therefore, a later extension of the framework can allow to address these and further issues, for instance, by establishing tools for supporting the definition of a suitable scope of system (I1), or implementing workshops in companies for the training of designers to promote their mindset (E2).

Thus, the scope and impact of the framework are delineated by the premises made. In this way, the framework has a clear focus without inhibiting a later expanding of the framework by further sub-phenomena or influence factors.

6.1.3 Context of application

After outlining the scope of the activities supported by the framework, in this subsection the context of the application is considered from the perspective of the type of the product and design process, as well as the users of the framework. Both provide essential boundary conditions for the evaluation of the framework for specific design projects and the selection of the users.

The type of the product can be described, for instance, by the domains involved within the development like *mechanical engineering*, *electrical engineering*, and *information technology* [JW07:2]. Within this thesis, the focus lies on mechanical engineering since the background of the author, as well as the projects accompanying this research, are mainly located in that domain. Also, the origin of most of the existing approaches analyzed within this thesis lies in this research field. Nevertheless, during the research, many contact points were identified with electrical engineering and information technology. The transfer of many existing approaches turned out to be appropriate in many cases, for instance, when developing modular software architectures for ensuring flexibility for changes. Although the framework mainly aims at the domain of mechanical engineering and has only been applied within this domain, it is considered promising to contribute further research towards a cross-domain approach.

Besides the type of the product, the type of the design process defines the context of application. For instance, design projects can deal with *original design processes*, *redesign processes*, or *variant design processes* [BC09:302ff.]. Since product architecture design can be relevant in various design situations, this framework shall not limit the scope to specific types of design processes. Therefore, the framework shall be applied to original design processes in which the product architecture arises de novo, as well as to redesign design processes or variant design processes in that existing product architectures provide the basis for possible adaptions. Furthermore, no limitation shall be made regarding the stage of the design process. In Sec. 2.4.1, it has been shown that product architecture design can be carried out at various points of time depending on the available information about the product. The framework shall strengthen the understanding of the possibility to integrate product architecture design at various stages of the process and support the implementation of approaches continuously (will be later shown by the second constituent of the framework).

The users of the framework can generally be divided into two groups: First, the framework shall support *product designers* in situations related to the determination of the product architecture, see Sec. 6.1.2. Thereby, *product designers* shall be considered as all functional roles related to designing, also including product managers and product planners. Second, *method designers* (from academia or design practice) can use the framework in order to identify and combine elements of existing PAD approaches to include these into new approaches. In that way, for both groups, it is assumed that the framework provides an overview of the field of PA approaches and enables the designers to implement these in new environments.

6.1.4 Intended plan for implementation

An intended plan for implementation of a new design support is essential in order to ensure the transfer of the support into application [BC09:142]. An implementation can occur, for instance, with paper-based descriptions of the approach, software tools to support its application, training programs for designers, workshops etc. [Bav18:51ff.]. The introduction of different means for implementation can occur step by step, for instance, first paper-based and later supported by a software tool while each step of implementation can supply feedback for further steps.

Within this thesis, the approach will be provided in the form of textual descriptions of the framework and the constituents supported by a prototype of a software tool to demonstrate the benefits of a data-based systematization of knowledge elements. Obviously, the description of the approach within this thesis mainly addresses researchers since the type of a scientific work does not comply with requirements from practice (like compactness and the focus on providing prescriptive knowledge). However, it is intended to provide a description that allows researchers to recognize the benefits and the necessity of introducing overarching approaches into design practice. Therefore, researchers shall be enabled to transfer the framework into industrial projects by implementing single elements as provided in the form of the three constituents described within this chapter. Moreover, the software demonstrator shall illustrate a possibility to easily formalize and access knowledge elements regarding product architecture design. In further works, the demonstrator shall be used to integrate new knowledge and apply these knowledge in design projects.

Obviously, further steps must be made in order to allow designers to make use of the framework more easily. Chap. 8 will describe this by an outlook of this research.

6.2 Overall organization structure of the framework

Until this point, the strain of this thesis has been built on the five fields of design research that allowed for a purposive analysis of existing approaches and a derivation of a methodical concept for the framework. However, the five hypotheses are *not* prepared in an application-oriented way that allows designers to benefit of the knowledge within typical design situations. Considering this, within this section an organization structure will be derived that defines three main constituents of the framework incorporating the hypotheses in an appropriate way for the application in design practice. Therefore, in Sec. 6.2.1, three scenarios will be depicted that define suitable starting points for the application of the framework. In Sec. 6.2.2, the integration of the three corresponding constituents will be described within the overall composition of the framework.

6.2.1 Scenarios for the framework's application

The five fields of design research have been proven useful to ensure comprehensiveness of the analysis of existing approaches from a scientific perspective. From an operational perspective, now, the challenge is to implement these insights into design practice considering the typical designers' situations. Therefore, following three scenarios are defined:

- **Recognizing PAD goals**
  Designers assess the relevance of implications of product architecture on product properties while planning products and clarifying design goals.
- **Integrating PAD into design processes**
  Designers define the most suitable stages within a design process to integrate product architecture design by considering the availability and use of product models within the design process.

- **Determining the PA**
  Designers determine the product architecture by analysis and synthesis of the product supported by principles and methods.

The basis for this definition provides the phenomenon model described in Sec. 4.1.2. Accordingly, Fig. 6.2 illustrates the three scenarios by highlighting which of the five sub-phenomena is considered within one scenario. The upper half highlights the central sub-phenomena of the situations in comparison to Fig. 4.3, the bottom half shows the sub-phenomena in comparison to Fig. 4.4. Therefore, the first scenario includes the consideration of PAD goal (Hypothesis 3). The second scenario covers the descriptive sub-phenomena of PA representation (Hypothesis 1) and PAD stage (Hypothesis 2). The third scenario includes the prescriptive sub-phenomena of PAD principle (Hypothesis 4) and PAD method (Hypothesis 5). However, the elements greyed out show that within the second scenario the PAD goals are relevant as well when integrating PAD into design processes. For determining the PA within the third scenario, additionally, the PA representations, the PAD stage, and the PAD goals are considered with a side focus.

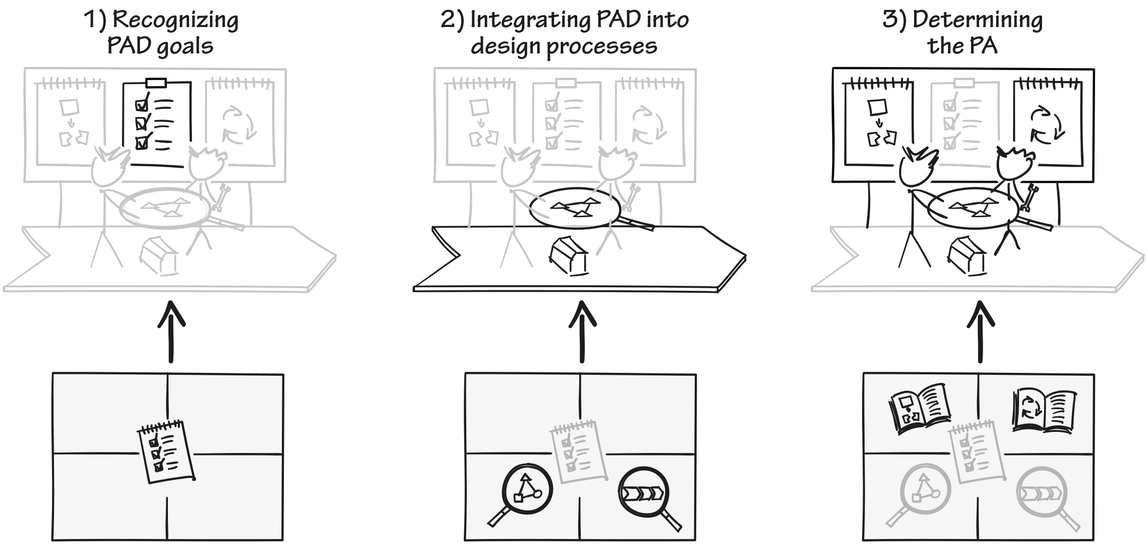


Figure 6.2: Scenarios for the framework's application according to the consideration of the five sub-phenomena

By these three scenarios, three typical fields for applications are described in that designers can be supported by the five hypotheses. The scenarios can occur independently from each other for what reason it is expedient to provide separated supports. The framework shall provide this support by including three constituents according to the three scenarios. The constituents can be applied independently from the others in order to support the single scenarios. However, in many cases, a combined application is appropriate what will be described in the following subsection.

6.2.2 Composition of the framework

Each constituent of the framework can be described by a particular purpose concerning the respective scenario defined above, the initial situation, the expected delivery, and the supporting means. An overview of these elements concerning the three constituents is provided in Tab. 6.1.

Table 6.1: Overview of the objective and approach of the three constituents of the framework

	Constituent 1	Constituent 2	Constituent 3
Purpose	Enable designers to recognize PAD goals relevant for a specific design project.	Enable designers to integrate PAD into design processes at the most suitable stages by the consideration of PA representations most appropriate.	Enable designers to determine the PA by applying PAD principles and PAD methods.
Situation	A product (assortment) or the intention for its development exists. Potentials of PAD for achieving design goals are not clear and shall be examined.	A design process or the need for one as well as defined PAD goals exist. The most suitable stage for integrating PAD into the process is not clear and shall be defined.	A process stage for addressing PAD goals is defined. Within that stage, the PA shall be determined according to the PAD goals.
Delivery	▪ a set of prioritized PAD goals for the present design project	▪ PAD stages within the design process in that the PA is considered explicitly ▪ PA representations to be used within the stages	▪ one or several concepts of the PA identified and evaluated by PAD principles and PAD methods
Means	▪ *PAD Goals Chart* (Sec. 6.3.1) ▪ Goals DB (Sec. 5.4.3)	▪ *Product Model Process Chart* (Sec. 6.3.2) ▪ Repr. DB (Sec. 5.2.3) ▪ Stages DB (Sec. 5.3.3) ▪ Goals DB (Sec. 5.4.3)	▪ *Basic PAD Method* (Sec. 6.3.3) ▪ Repr. DB (Sec. 5.2.3) ▪ Goals DB (Sec. 5.4.3) ▪ Principles DB (Sec. 5.5.3) ▪ Methods DB (Sec. 5.6.3)

The supporting means are of two types. First, general guidelines are proposed in the form of the *PAD Goal Chart* (1), the *Product Model Process Chart* (2), and the *Basic PAD Method* (3). These will be described within Sec. 6.3. Second, databases (DBs) of knowledge elements that are provided by the software tool (as described in Chap. 5). The usage of the software tool is described in detail in Sec. 6.4.

The application of the constituents can occur in different orders within a design project, whereas the constituents can be applied iteratively. Fig. 6.3 shows (on the left side) a possible order in which the constituents can be applied. Therefore, the first constituent allows to derive relevant PAD goals as a starting point for the explicit consideration of PAD within the design projects. This provides the input for the second constituent, in which appropriate PAD stages are defined by considering most appropriate PA representations to address the relevant PAD goals. Finally, the PAD stages guide the determination of the PA within the design process by applying the third constituent. On the right side of Fig. 6.3, it is illustrated that during the application of the constituents all five kinds of knowledge elements from the knowledge base are used.

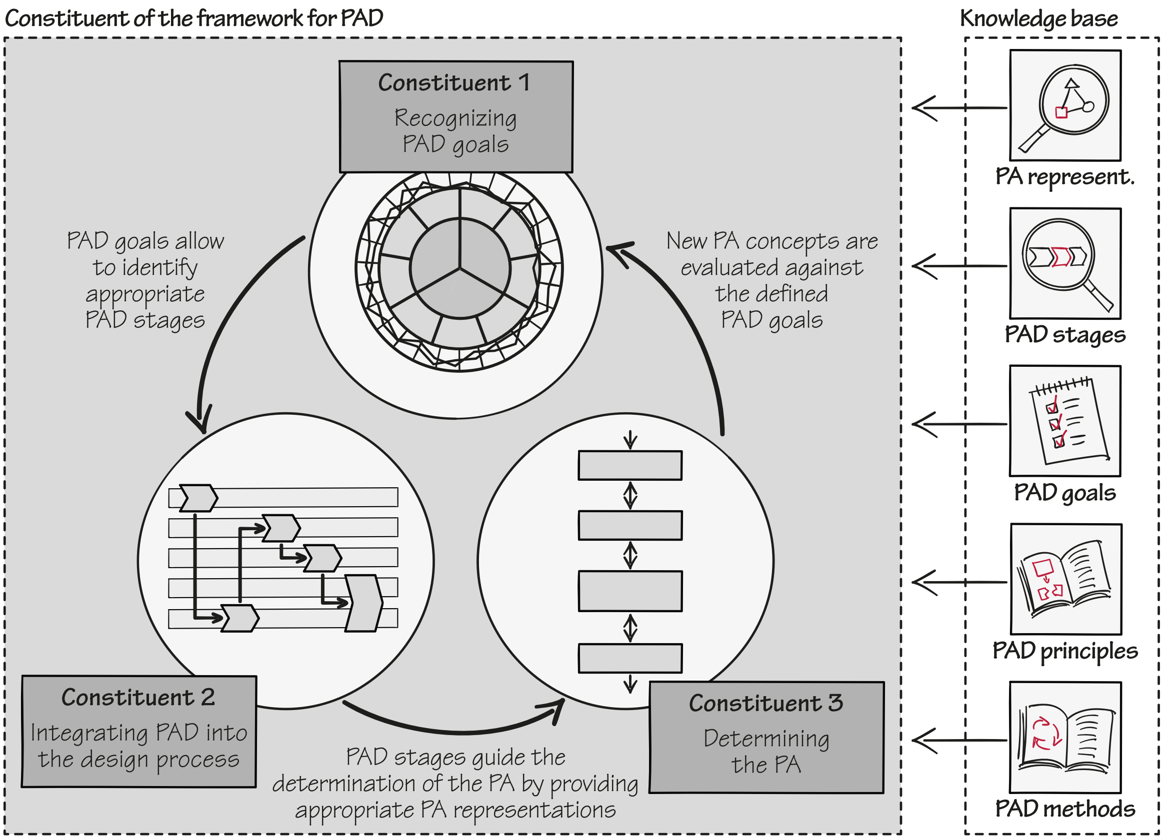


Figure 6.3: Organization structure of the constituents of the framework

The here described order of the application of the constituents is especially suitable when the level of experience of the designers is low, and only a few PAD approaches are known. In that case, the application of all constituents allows to systematically address all critical issues defined within the phenomenon of product architecture design. However, in other cases, the initial situation can provide preliminary works, for instance, when PAD goals as well as a specific PAD stage are predefined. In that case, the application of the framework can start with the third constituent. Moreover, the framework can be passed through iteratively. For instance, if doubts arise during the application of the third constituent concerning an appropriate definition of the PAD goals, these can be redefined in the first constituent. Equally, a redefinition of PAD stages can be required when during the application of the third constituent it becomes apparent that further considerations of other product models are necessary to address the PAD goals appropriately.

Thus, this section has provided an overview of the scenarios and the corresponding constituents of the framework. The subsequent section provides further insights into the way of application of the three constituents and introduce the supporting means.

6.3 Constituents of the framework

The constituents of the framework provide an operational basis of accessing knowledge of product architecture design. In this section, the constituents are described in detail in order to allow to understand their purpose, way of application, and deliveries.

6.3.1 Constituent 1: Recognizing PAD goals

The definition of design goals is a central activity for recognizing the relevance of PAD. Thereby, the key problems are, first, that designers do not recognize possible implications of product architecture (at all), and second, that these implications are not set in relation to the company's strategy in order to allow prioritization. Therefore, the first constituent aims at illustrating the variety of goals and allowing product planners, designers, and other stakeholders to prioritize these for specific design projects. The premises for this have been made within the preceding chapters as follows:

- Design goals are a central element serving for monitoring the success of designing, see Sec. 2.1.1.
- Design goals describe specific product properties whereas PAD goals only describe those that are affected by the product architecture, see Sec. 2.2.3 and 2.5.
- A prioritization of design goals can often only be made with regard to the company's strategy, see Sec. 2.2.3.

Based on these premises, Hypothesis 3 postulates that the recognition and prioritization of PAD goals can be made on the basis of strategic goals. Therefore, within Sec. 5.4 an analysis of PAD goals described in literature has been carried out resulting in a list of 27 design goals possibly relevant to product architecture design. These premises feed into the first constituent giving designers access to existing knowledge about PAD goals.

The central element for this is provided by the *PAD Goal Chart* as illustrated in Fig. 6.4. It combines the viewpoint of strategic goals of the company with possible PAD goals within a multilayered spider diagram. According to the strategic design goals derived in Sec. 5.4.1, on the inner layer the three strategic fields are shown (*value proposition*, *customer interface*, and *infrastructure management*). On the middle layer the strategic goals are displayed that are allocated to the strategic fiels. An overview of these two layers have been given in Tab. 5.3. Finally, on the outer layer, the 27 PAD goals are arranged. Within this illustration, only an exemplary section of PAD goals is included. The full scope of PAD goals can be found within a blank version of the *PAD Goal Chart* in Appendix E.2 in Fig. E.1 and the detailed description of the PAD goals in Tab. E.2.

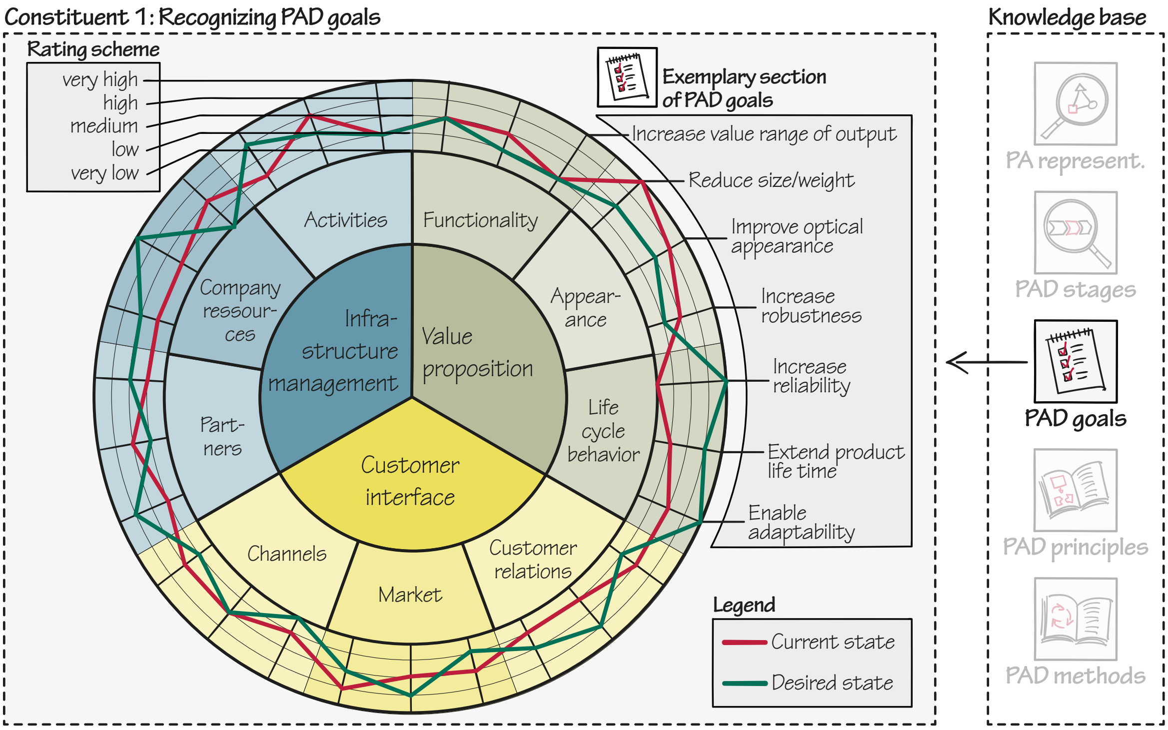


Figure 6.4: The *PAD Goal Chart* for supporting the recognition of PAD goals

In this way, the 27 PAD goals are structured hierarchically regarding their relevance to the strategy of a company. This categorization shall ensure that designers keep the whole range of PAD goals in mind and shall avoid a fixation on single goals. The graphic representation within the spider diagram aims at supporting the communication between different stakeholders of the company on the prioritization and monitoring of PAD goals during the whole design process. For illustration, in Fig. 6.4 a red and a green line are included. The red line represents the evaluation of a predecessor product against the fulfillment of the 27 PAD goals (on a scale from *very high* to *very low*). In comparison, the green line represents the defined target for the fulfillment of the 27 goals for a new product to be designed. The gap from the red line to the green line visualizes the need for improvement.

The categorization regarding the company's strategy shall highlight that product architecture design can contribute to different strategic focuses of a company. This is important when goal conflicts arise. Such a goal conflict appears when two PAD goals are relevant, but the solutions for addressing the goals are not compatible. For example, when the focus is laid on the strategic goal *physical appearance*, components of the product can be integrated to avoid interfaces in order to increase *robustness*. However, by this, goals regarding other strategic fields like *activities* can be affected negatively since the product finally will comprise a reduced modularity. To address these goals, it might be beneficial, to separate components in order to obtain modules according to the extents that are developed jointly during the design process. In those cases, the *PAD Goal Chart* cannot support the solving of the goal conflicts, but it can illustrate the classification of the concerned PAD goals regarding the strategic goals. This can support the reconsideration of the prioritization of the goals by balancing the overarching strategic goals against each other. When, for instance, alternative business cases for a planned product are considered (e.g., a business case with a high priority of the *customer interface*), those PAD goals most relevant to this business case can be primarily addressed.

Obviously, the diagram cannot substitute further tools for requirements management during the design process. However, for supporting the conceptualization stage, it provides an expedient tool for communication between the stakeholders as it is proposed by various approaches from strategic product planning, cf. [Vaj14:100ff.] [SAG+17:44ff.] [Wie14:5ff.] [SCR+18:1951ff.]. In this way, it can support the planning of new products and support the evaluation and comparison of predecessor products or new product concepts.

In order to apply the *PAD Goal Chart* appropriately, designers can pass through the following three steps:

1. **Prioritization of strategic goals**
   Strategic fields and strategic goals on the two inner layers of the chart are prioritized. According to established approaches, cf. [LI14, OP10, Ost04], a company can hardly be successful in different strategic fields to the same extent. Thus, a definition of the central strategic field and strategic goals shall ensure a clear focus in the next steps. This prioritization needs to be made generally, without explicitly discussing the possible solutions for addressing the strategic goals. The basis for this can be provided by the analysis of predecessor products. The result can be definition of alternative business cases prioritizing different strategic fields and strategic goals.

2. **Prioritization of PAD goals**
   The PAD goals on the outer circle have to be recognized in order to rate their relevance within the considered design project. The prioritization can be supported by the database of PAD goals that provides detailed descriptions of the goals, see Sec. 5.4.3. The result of the prioritization can be drawn into the radar chart on a scale from *very high* to *very low*. In order to facilitate the rating, beforehand, those PAD goals assigned to strategic goals identified within the first step can be left out.
3. **Define goal collectives**
   In order to tackle the PAD goals, it can be suitable to define goal collectives that are addressed within the elaboration of different product architecture concepts. Especially, when the number of PAD goals with a high importance is great, it will be difficult to focus on all PAD goals at the same time. Then, collectives including PAD goals allocated to neighboring strategic goals can facilitate the concept elaboration. Later, the different concepts can be compared and, if applicable, combined.

Overall the result of this constituent is a definition of one or several collectives of PAD goals that shall be addressed within the design project. During the course of designing, a redefinition of PAD goals within the goal chart can be made. Therefore, the chart provides a tool continuously used in the design process for the clarification of the task and the evaluation of product concepts. The comparison of product concepts can be supported by inserting multiple lines representing the prioritization of PAD goals of different stakeholders or the evaluation of different product concepts to be compared.

6.3.2 Constituent 2: Integrating PAD into the design process

The central objective of the second constituent is to enable designers to define a design process including the processed product models in a way suitable for addressing PAD goals. To define design processes appropriate for PAD, within the preceding chapters, premises have been elaborated that allow to make simplifying assumptions on design processes. Summarized, these are:

- The quality of a design process mainly depends on its appropriateness to allow designers to achieve specific design goals, see Sec. 2.2.2. Thus, when the PA is relevant to a design project, the consideration of the PA shall be explicitly integrated into the design process.
- The analysis and synthesis of a product regarding specific PAD goals is carried out on the basis of PA representations (specific product models) whereas these often only allow to address a limited number of PAD goals, see Sec. 2.3.

- The availability of appropriate PA representations depends on the stages within PAD processes since these are mainly defined by the processed information about the product, see Sec. 2.2.2.

Following the argumentation of these premises, Hypothesis 1 and Hypothesis 2 formulated the idea that an overarching understanding of PA representations (in the form of basic PA levels) and an overarching understanding of PAD stages (in the form of basic design stages) can allow designers to identify appropriate PA representations at appropriate points in time within a design process. The combination of these approaches provides the basis for the second constituent that combines the perspectives of PA representations with that of PAD stages.

The *Product Model Process Chart* as shown in Fig. 6.5 provides the central support for this constituent. The horizontal rows provide the basis for modeling the design process. Therefore, each row represents a basic design stage (respectively product models) that are possibly run through within a design process according to the process modeling approach of Gericke and Maier [GM11], see Fig. 2.4. Thereby, the five highlighted rows represent the five PA levels. Modeling the process across these rows allows to highlight which product models are considered in which stages of the process.

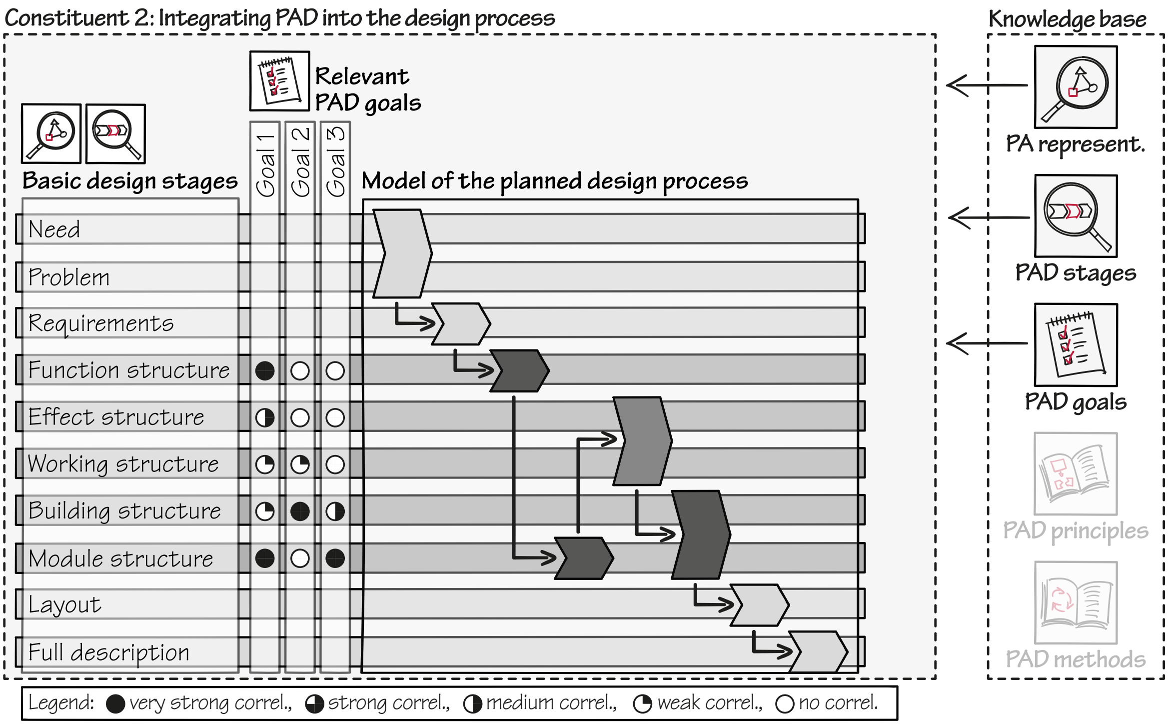


Figure 6.5: The *Product Model Process Chart* for integrating PAD into the design process

On that basis of this process model, it can be identified which stage is appropriate for addressing the PAD goals relevant within the design project. Therefore, heuristically determined correlations between PAD goals and PA levels are used that are based on the PAD principles (see Sec. 5.5.3) included in the database. Each PAD principle is assigned to PAD goals and PA levels. By evaluating all these correlations, for each PAD goals it can be determined which PA level is appropriate for its addressing, i.e., on which PA level PAD principles are available. In this way, the correlations between the 27 PAD goals and the 5 PA levels as calculated by the software tool can be used here for inserting the relevant PAD goals as columns to the chart (in Fig. 6.5 exemplary named as *goal 1*, *goal 2*, and *goal 3*). For this, the *PAD Goals/Levels Chart* is used as shown in Tab. E.5 in Appendix E.5. It contains a plot of the correlations between PAD goals and PA levels. For instance, for the PAD goals *improving process organization*, the correlations comply with those exemplary illustrated for *goal 1* in Fig. 6.5. From this, it can be concluded, that this PAD goal can be particularly addressed on the level on the level of the function structure and the module structure corresponding to the third and fourth stage within the illustrated exemplary design process within the chart.

Therefore, the *Product Model Process Chart* is a tool for the analysis and refinement of existing processes. The focus is not on the definition of new processes. This is due to the high number of aspects that have to be considered within the process definition. For instance, various other process properties besides the achievement of PAD goals have to be considered that require other process models, for instance, to evaluate the efficiency of the process or the effort for the included resources. Moreover, in many companies design processes are established over a long time, and the process executors like designers are accustomed to these processes. Thus, to apply the *Product Model Process Chart* existing processes are required that are analyzed and refined.

The application of the constituent can be described by five steps that include the utilization of the database of PAD goals (see Sec. 5.4.3) as well as the database of PA representations (see Sec. 5.2.3):

1. **Process analysis**
   The existing or planned design process is charted within the *Product Model Process Chart* by allocating the stages to the prescribed basic design stages.
2. **PAD Goal analysis**
   Relevant PAD goals (as identified by support of the first constituent) are entered as columns into the chart in order to illustrate the mapping of PAD goals with the PA representations, see Tab. E.5.
3. **Process assignment of goals**
   PAD goals are assigned to design stages that include product models that allow to analyze and synthesize the PA accordingly.

4. **PA representation definition**
   For each stage, specific PA representations can be defined that allow to analyze and synthesize the PA appropriately. Therefore, the database of PA representations can be used to identify PA representations that correspond to the specific PAD goals.
5. **Process refinement**
   If required, the design process has to be refined by modifying or adding stages in order to ensure that all PAD goals can be addressed on appropriate PA levels.

Overall, the result of the execution of the steps is a modified design process that ensures to address the relevant PAD goals. In this way, the point of time when the PA is considered is defined explicitly, and therefore a late consideration can be avoided. For this, the application of the *Product Model Process Chart* provides useful support that creates transparency of the dependencies between design stages, PA levels, and PAD goals. The databases provide the required information about which relations between product models and PAD goals allow to determine the PA appropriately.

Within the next step, at each of the stages defined in the chart, the product architecture needs to be considered. For this, the third constituent can provide support for determining the product architecture according to the defined PAD goals.

6.3.3 Constituent 3: Determining the product architecture

The key objective of the third constituent is to support designers when determining the product architecture. Whereas the first two constituents lay the focus on descriptive elements supporting the *understanding* of the design goals and the design process, this constituent is of a prescriptive character, i.e., provides knowledge to *determine* the product architecture. Therefore, following premises have been derived before:

- The prescriptive knowledge required within design situations can be differentiated in knowledge related to the product and the design process, see Sec. 2.1.3.
- Product related knowledge regarding the product architecture can be provided as design principles respectively PAD principles, see Sec. 2.2.4 and Sec. 2.6.
- Procedure related knowledge is based on similar reoccurring patterns of problem-solving that can be formulated and applied as design methods respectively PAD methods, see Sec. 2.2.5 and Sec. 2.7.

On that basis, Hypothesis 4 and Hypothesis 5 consider that literature provides prescriptive knowledge in the form of PAD principles and PAD methods. Systematizing this knowledge in an overarching framework can support designers in accessing the knowledge required according to the PAD goals in focus. Therefore, in Sec. 5.5 and Sec. 5.6, a meta level for PAD principles and PAD methods has been elaborated, describing basic PAD principles and activities of a *Basic PAD Method*. Within this constituent, a prescriptive approach shall be presented that allows to access and apply this prepared knowledge in order to enable designers to achieve a customized PAD approach.

The central element of this constituent provides the *Basic PAD Method* that provides a procedure in accordance with the activities supported by existing approaches, see Sec. 5.6. The steps of the procedure, as well as the knowledge elements that can be integrated, are illustrated in Fig. 6.6.

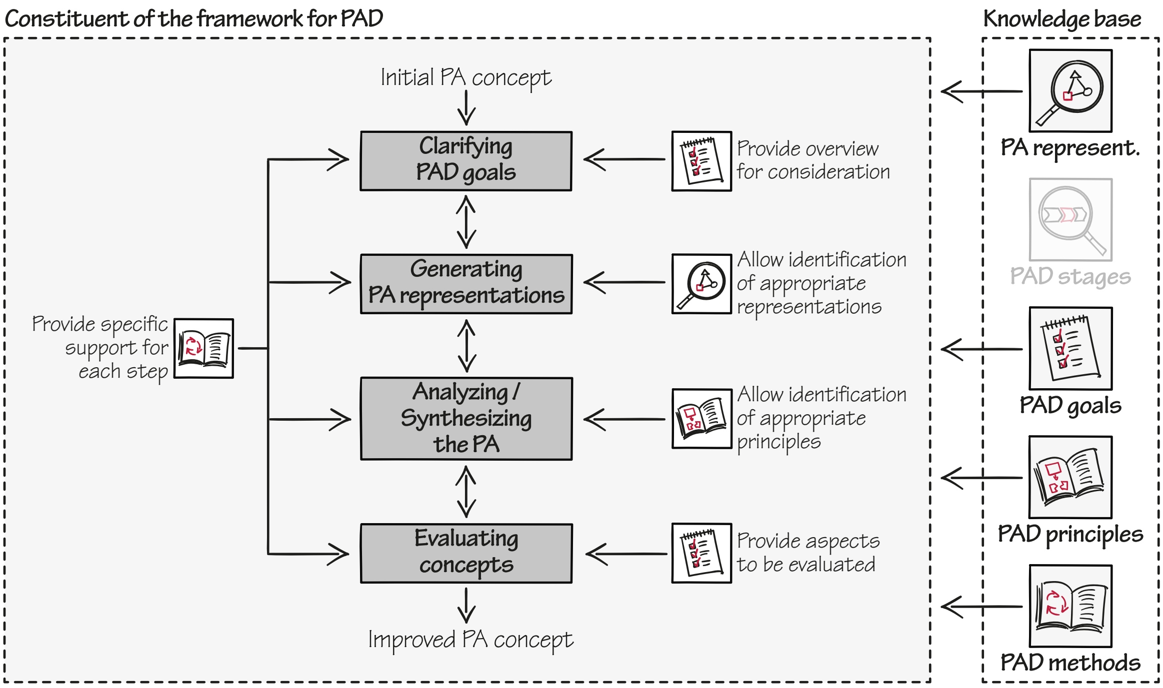


Figure 6.6: The *Basic PAD Method* supported by specific knowledge elements included within databases (DB)

The *Basic PAD Method* describes the fundamental activities that can be passed through within product architecture design. In the abstract way of the description of the activities, the procedure is supposed to cover the main activities that are carried out in the existing PAD approaches. Each activity provides the basis for a further specification. Thus, for each step, specific PAD methods (see Sec. 5.6.3) can be integrated from literature to include specific procedural knowledge. Besides this, PAD goals (see Sec. 5.4.3), PA representations (see Sec. 5.2.3), and PAD principles (see Sec. 5.5.3) can be accessed within the procedure in accordance with the specific constraints of the process. For instance, depending on the goals that are defined in the first step, specific PA representations and PAD principles are accessed during the following steps resulting in a PAD approach customized to the specific design situation.

In detail, the steps of the procedure include the following activities:

1. **Clarifying PAD goals**
   In preparation for a purposive product architecture design, the PAD goals are defined to be addressed within this stage. These goals can be adopted from preceding activities for goal clarification, for instance, the application of the first constituent for defining PAD goals. However, of these possibly high number of relevant PAD goals, a limited selection of goals must be made according to the focus of the current stage as defined within the application of the second constituent.
   For a further clarification of the goals, specific PAD methods (see Sec. 5.6.3) can be applied that allow to precise the definition of specific PAD goals (see Sec. 5.4.3).
2. **Generating PA representations**
   The design of the product architecture must be made on the basis of an appropriate PA representation. Therefore, within the current state of the design process, specific information about the product is available that provides the basis for the generation of a PA representation. Therefore, the second constituent can be used to illustrate specific stages to basic PA levels. This can provide the basis for identifying PA representations most appropriate to address the defined PAD goals.
   For supporting the generation of specific PA representations (see Sec. 5.2.3) various specific PAD methods exist (see Sec. 5.6.3) that can be applied within this step. These methods guide the designers in creating a PA representation suitable for the design goal on the basis of the available information about the product.
3. **Analyzing & synthesizing the PA**
   Aiming at the development of new PA concepts, within this step, the analysis and synthesis of the product architecture is carried out. The basis for this provides the initial product architecture as modeled within the PA representation. This architecture is varied in a way promising to achieve the defined PAD goals. The analysis aims at assessing whether the variations of the PA contribute towards the fulfillment of the goals.
   The main support for this step is provided by PAD principles (see Sec. 5.5.3). These supply designers with the product knowledge, i.e., the knowledge about relations on how specific arrangements of the product architecture affect PAD goals. Furthermore, specific PAD methods (Sec. 5.6.3) can be applied that provide the procedural knowledge to carry out activities of analysis and synthesis.
4. **Evaluating concepts**
   Within the evaluation, it must be decided whether the previous activities of PAD have led to satisfying results regarding the fulfillment of the PAD goals. If not, iterations must be made, for instance, by redefining PAD goals and/or PA representations, and

applying other PAD principles.

As support, specific PAD methods for evaluation (see Sec. 5.6.3) can be applied that provide procedures and means to make decisions on the overall quality of the product architecture. Equally to the first step, the *PAD Goal Chart* and the procedure described within the first constituent (see Sec. 6.3.1) can provide a general support for this step, and therefore, provide a method itself.

The order in which the steps are illustrated in Fig. 6.6 and described here mainly comply with the standard procedure of problem-solving of Daenzer and Huber [DH99:99] [VDI04:27f.], see Fig. 2.8. However, depending on the specific design situation, the steps can also be carried out in a different order. For instance, the generation of a PA representation can serve as starting point if PAD goals have not been defined before. Then, a PA representation can be generated and evaluated in order to define PAD goals. After that, the steps can be carried out in the order described above.

To illustrate the application of the third constituent, a possible scenario shall be explained included specific knowledge elements used during the execution of the four steps. As example the goal *improving process organization* shall be taken since it is addressed by various existing PAD approaches. For instance, in *Modular Function Deployment* of Erixon it is referred to as the module driver *process and/or organization re-use* [Eri98:72]. In the following, it will be described which knowledge elements can be accessed by the *Basic PAD Method* through the software tool. In each case, one example will be given, although in many cases further elements can be identified.

1. **Clarifying of PAD goals:** Supporting the first step, the first constituent allows to clarify the PAD goals by selecting and prioritizing out of 27 possible PAD goals. In this case, for the goal mentioned above methods can be identified for clarifying the goal.
   - **PAD goal:** *improving process organization* (see PAD goal card in Fig. 5.3)
   - **PAD method (supporting this step):** *Business Process Modeling* (a generic method for modeling design processes with a focus on information flows between teams or firms)

   Therefore, the approach allows to go into further detail to define the goals and provides supporting methods for clarifying these specific goals.
2. **Generating PA representations:** Based on the specified PAD goals, PA representations can be chosen and generated supported by corresponding PAD methods. For this, in many cases, the PA level has been defined by the second constituent. In this case, is identified as appropriate to consider the function structure.

- **PA representation:** *Flow-oriented Function Structure* (for PA representation card see Fig. 5.5)
- **PAD method (supporting this step):** *Modular Design Methodology*

The selection of PA representation and PAD method for supporting this step have to be made considering the specific boundary conditions.

3. **Analyzing & synthesizing the PA:** For the determination of new PA concepts, the focus lies on the provision of PAD principles. PAD methods can be applied to support the deployment of the principles. Examples for the PAD goal *increase the degree of individualization* are:
   - **PAD principle:** *Integrate design units into modules with strong interdependencies* (for PAD principle card see Fig. 5.9)
   - **PAD method (supporting this step):** *Integration Analysis of Product Decomposition*

   In many cases, the tool provides a huge number of principles and methods. The designer has to decide within the individual case which of these are appropriate for the specific task.
4. **Evaluating concepts:** Finally, the generated concepts can be evaluated against the defined PAD goals for that PAD methods can be selected.
   - **PAD goal:** *improving process organization*
   - **PAD method (supporting this step):** *Integration Analysis of Product Decomposition*

   After evaluating the concepts, it have to be decided on the next steps: to iterate the application of the *Basic PAD Method*, for instance, by applying further principles or by varying the applied PA representations, or to choose the PA concepts for further development.

Thus, the example has shown that the third constituent allows to implement knowledge elements in the form of PAD goals, PA representations, PAD principles, and PAD methods customized for a specific design task. Thereby, the designers are enabled to search and select knowledge elements within the knowledge base provided. The novelty of this approach is that the available knowledge is not restricted to specific cases, for instance, for single PAD goals, but covers a comprehensive viewpoint on product architecture design.

Whereas in this part, the access to the knowledge elements has not been described in detail for the three constituents, the following section will illustrate the way of accessing the knowledge with the support of the software tool.

6.4 Software demonstrator for supporting knowledge provision

Within the preceding section, the constituents provided an application-oriented access to knowledge elements of product architecture design. To make this knowledge easily accessible, a software demonstrator has been developed for representing and using the cross connection between the different knowledge elements. This section aims at presenting the functionality of this software tool to complete the framework for product architecture design. Therefore, in Sec. 6.4.1 and Sec. 6.4.2, the scope and communication structure of the software demonstrator will be outlined. Based on that, Sec. 6.4.3 will illustrate the possibilities of access to the knowledge elements according to the application of the before described constituents. Finally, in Sec. 6.4.4, the level of development of the software tool as well as of the included knowledge base will be summarized.

6.4.1 Scope of the software demonstrator

In Chap. 5 it has been shown how knowledge elements can be extracted from existing PAD approaches. For doing this, for each kind of knowledge element a meta structure has been deployed that allows for a classification of the knowledge, and allows for a standardized formalization of the knowledge. As a result, it has been demonstrated how PA representations (see Fig. 5.3), PA levels (see Fig. 5.5), PAD goals (see Fig. 5.7), PAD principles (see Fig. 5.9), and PAD methods (see Fig. 5.10) can be provided in the form of profile cards each comprising the information related to one knowledge element as well as the links to knowledge elements of other kinds.

The preceding section has outlined how these knowledge elements can be used during the application of the three constituents. Each of the constituents integrates the application of different types of knowledge elements. For this, a purposive access to these elements is required that shall be provided by the tool. Accordingly, the tool is structured into three access interfaces, each supporting one constituent. Starting from these access interfaces, designers are guided to access the knowledge elements required, i.e., the profile cards. In this way, various ways are possible, to access the knowledge elements, see Fig. 6.7.

Overall, eight interfaces exist in the software tool: three access interfaces and five interfaces according to the knowledge elements within the knowledge base. Each of the interfaces represents a specific view of the PAD knowledge described before: The PAD Goal Chart supports the first constituent (recognizing PAD goals), the PAD Goals/Levels Chart supports the second constituent (integrating PAD into the design process), and the PAD Knowledge Filter supports the third constituent (determining the PA). Each

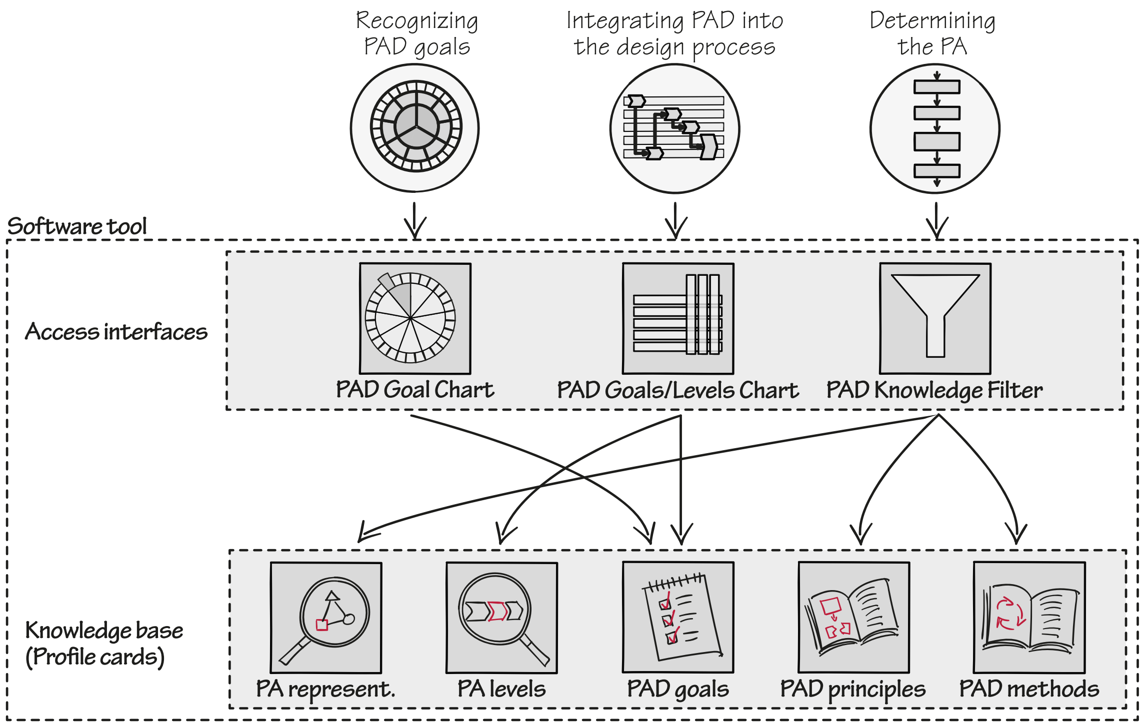


Figure 6.7: Structure of the software tool

of these three interfaces uses or refers to data of the databank supplying information about PA representations, PA levels, PAD goals, PAD principles, and PAD methods.

The core value of the software tool is the possibility to present the knowledge in a clear way and to filter the content. For this, various relations between the knowledge elements are stored in the database – relations that cannot be provided paper-based collections. For instance, a principle is related to PAD goals, to PA levels, to PAD methods, and to literature (see Fig. 5.9). Therefore, the overview presented in Tab. E.3 only includes a small amount of the actually required data to access the knowledge.

6.4.2 Communication structure of the software demonstrator

Due to the before described necessity of a database and various different interfaces to the data as well as the requirement to make the data accessible to the scientific community, the software is implemented as a web-based internet application. The web-based technologies allow to develop individual web pages that can be accessed via every web browser while the data can be stored on a server with a MySQL database. Accordingly, the structure of the application and the process of request processing is shown in Fig. 6.8.

The user interface of the tool is provided by a web browser. Via the URL *http://pad.ik.ing.tu-bs.de* the web pages of the tools can be accessed. These web pages are listed in the bottom

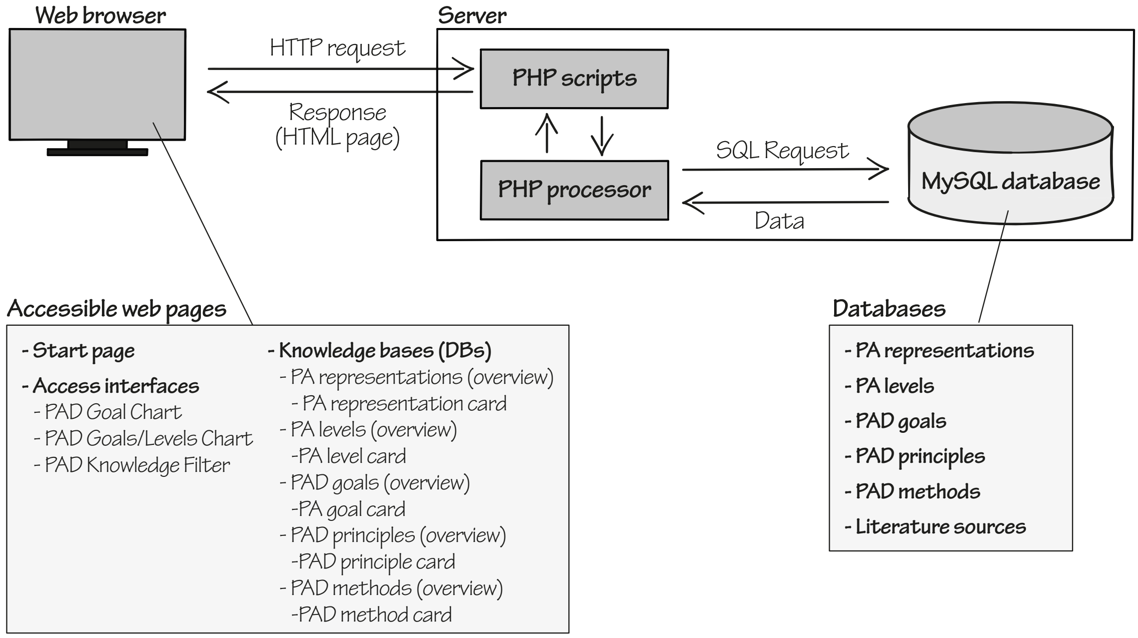


Figure 6.8: Request processing of the software demonstrator

left of Fig. 6.8, compare Sec. 6.4.1. By using these web pages, requests can be sent to the web server, for instance, by searching for PAD principles. The request is processed on the basis of PHP scripts that allow to send queries to a MySQL database that contains the PAD knowledge in the form of tables. Answering the query the database provides the data to the PHP processor that sends a response (as a HTML page) back to the browser.

6.4.3 Usage of the software demonstrator

The interface of the tool is provided by web pages displayed in a web browser. After calling the URL *http://pad.ik.ing.tu-bs.de* the user is directed to a start page as shown in Fig. 6.9.

In the top, the navigation menu is shown allowing to select on of the three access interfaces or one of the five databases from a drop down menu. The main section of the pages shows the start page describing the background of the thesis in short, providing a link to the thesis, and illustrating the three access interfaces as well as the five databases.

Whereas the representation of the PAD knowledge in the databases has already been described in Chap. 5, in the following, the three access interfaces will be introduced. Therefore, the description will follow the order of the three constituents as described in Sec. 6.3.

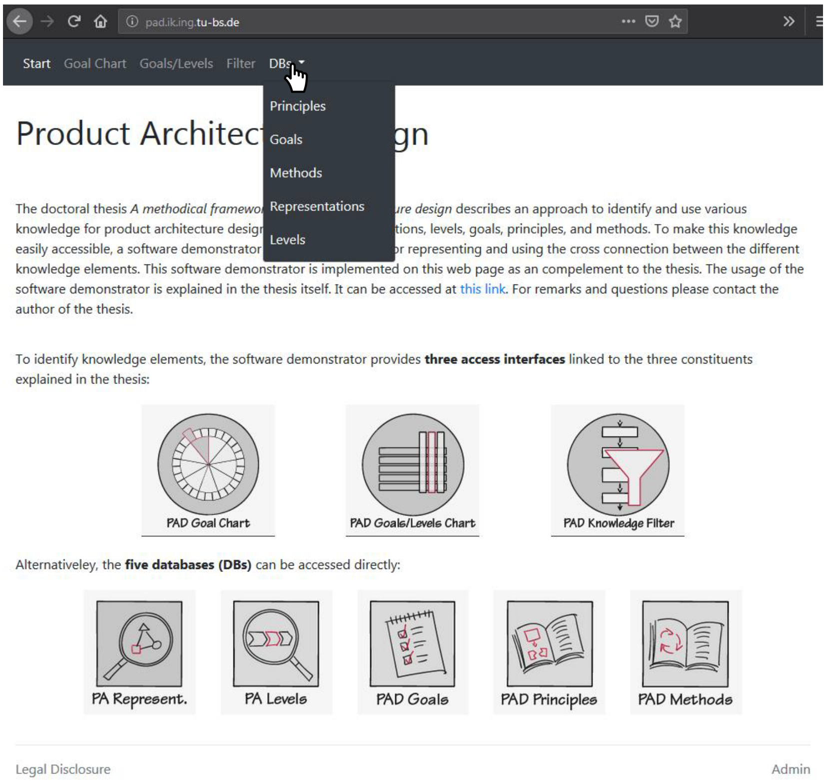


Figure 6.9: Screenshot of the start page of the software demonstrator

For supporting the **first constituent** for recognizing PAD goals, the framework proposes to use the *PAD Goal Chart* (see Fig. 6.4). The tool supports this by illustrating the complete chart including the 27 PAD goals, see Fig. 6.10. By selecting single PAD goals, the goal cards can be accessed in order to receive the description of the PAD goals, and if required, further related PAD methods allowing to clarify the goal. In this way, the tool provides an accompanying guidance for prioritizing goals by the provision of further information.

The **second constituent** for integrating PAD into the design process has been described by using the *Product Model Process Chart* (see Fig. 6.4). The chart allows to assign specific stages of the design process to basic design stages that include the basic PA levels. By mapping the relevant PAD goals to the levels, designers are allowed to identify stages appropriate to integrate the consideration of product architecture regarding this goals. To apply this constituent, designers require to access the information about correlations between PAD goals and PA levels. In order to avoid that designers have to examining the goal cards of each addressed PAD goal (see Fig. 5.7), the tool provides an overview of all correlation within one table. The scope of the goals included in the table can be filtered. Thus, as shown in Fig. 6.11, the tool can allow for reading out those correlations for a selected group of goals that are relevant to the specific case.

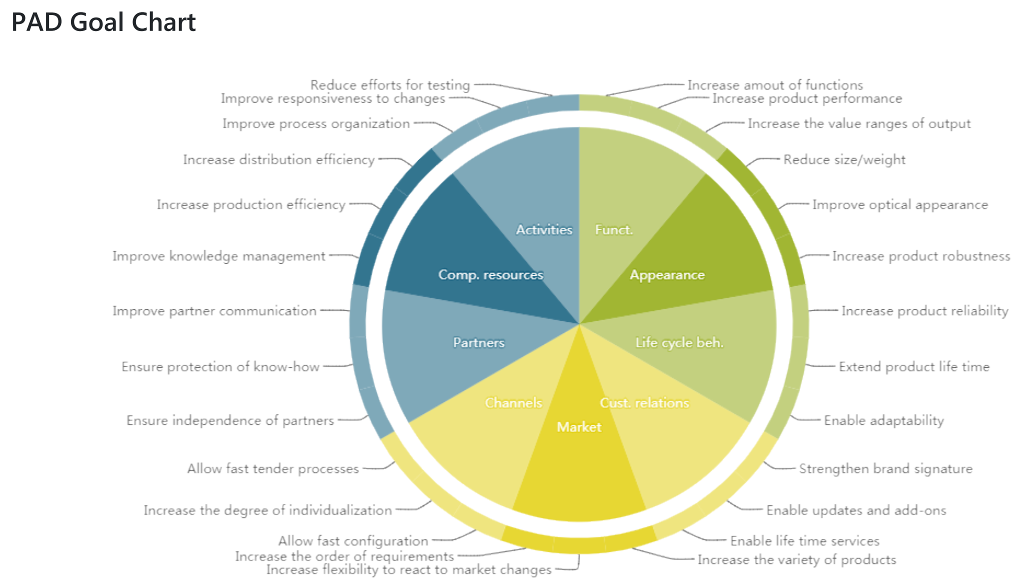


Figure 6.10: Screenshot of the *PAD Goal Chart* within the software tool

The entries within the cells of the table (from *very strong correlation* to *no correlation*) are computed by the strength of principles' correlations to this levels and the strength of these principles' correlations to the PAD goal, see further Appendix E.5. Therefore, the table provides an current snapshot of the correlations based on the principles currently included in the database at the date of reading out for this thesis. In further works, when more principles will be added, also the correlations table will be updated automatically in the tool.

The **third constituent** is probably the constituent that most depends on the use of the software tool. The *Basic PAD Method* only provides a generic approach that needs to be specified in each case. The specification is made by reading out PA representations, PAD principles, and PAD method. For this, the tool provides a filter of knowledge elements that allows to extract those knowledge elements most appropriate for the specified boundary conditions. These conditions are defined, at the current state of the demonstrator, by the relevant PAD goals and the PA level that can be defined by the first and second constituent. After selection these, the designers can access the PA representations, PAD principles, and PAD methods most appropriate, see Fig. 6.12.

As described before, the output of the tool might probably include various elements. For instance, for addressing the PAD goal *improving process organization* on the level of the working structure, eight PAD principle are provided. In that case, the principles are ordered according to the strength of the correlation to the PAD goal indicating the supposed probability of suitability. Then, the designers task is to decide on the selection of principles to be applied, or examining the applicability of all of them. In

PAD Goals/Levels Chart

Filter goals

Level	Reduce size/weight	Increase product robustness	Increase the variety of products	Allow fast configuration	Increase production efficiency	Improve process organization
Function structure	◔	◑	●	●	◑	●
Effect structure	◔	◑	●	◑	●	◑
Working structure	●	●	●	◑	●	◔
Building structure	●	●	●	●	●	◔
Module structure		◑	●	●	●	●

Legend:
○ main focus, ◑ side focus, ● not addressed

Figure 6.11: Screenshot of the *PAD Goals/Levels Chart* within the software tool

future extensions of the software tool, further criteria like *effort of application* can be added to facilitate the selection of knowledge elements

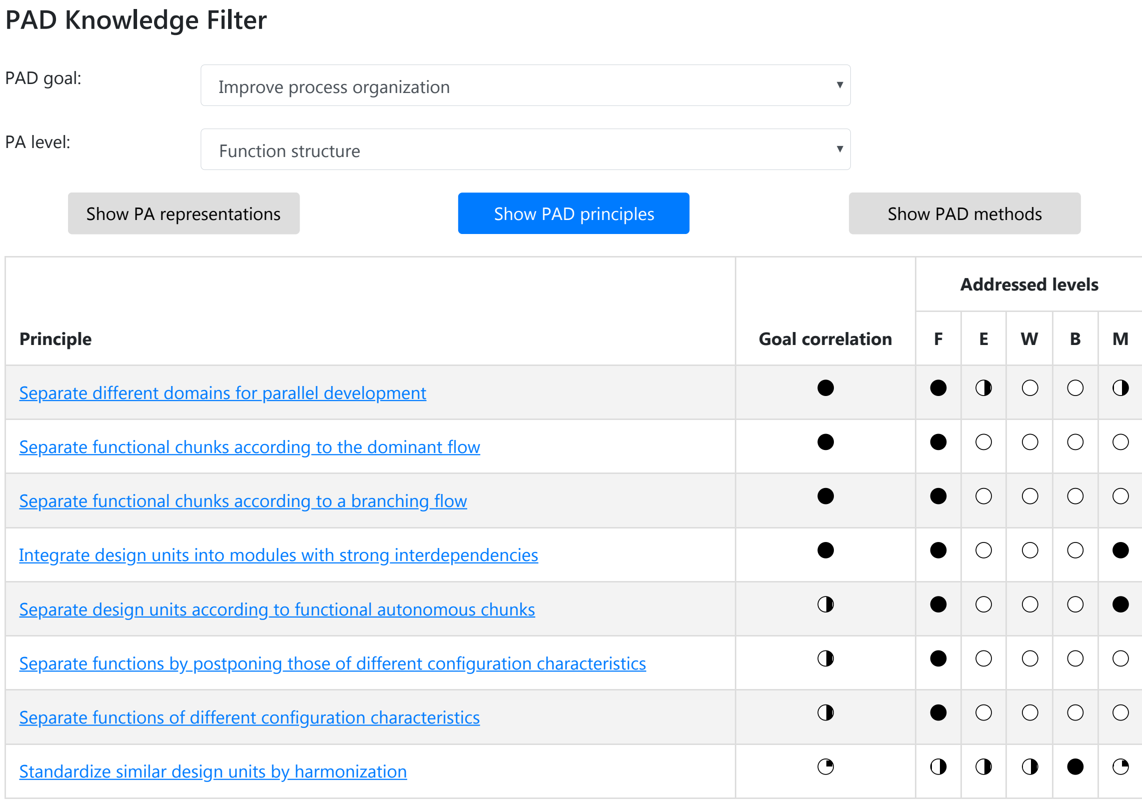
In this way, each of the three access interfaces allows designers to take a specific viewpoint on the knowledge elements. The knowledge elements themselves are described in the form of standardized profile cards that provide the knowledge in easily accessible formats. An example of the application of the tools will be described in the case studies in Chap. 7. Exemplary screenshots of the example in Sec. 7.2 are shown in Appendix F.

However, the state of the deployment of the tool as well as the scope of the knowledge base are limited at the point of time of publishing this thesis. Therefore, the following subsection shall summarize the state of implementation.

6.4.4 State of implementation

The software tool as described in this section is a demonstrator that serves for illustrating the applicability of the framework as proposed in this thesis. However, the tool does not claim to be fully developed neither in regard to the completeness of the included knowledge elements nor the application comfort. Therefore, finally, its limitation shall be outlined.

Regarding the scope of the included knowledge, the tool comprises the knowledge elements described in Chap. 5 plus further elements from the approaches listed in Tab. D.1. In this way, various established PAD approaches are included that cover topics like modularization, platform design, and integration. Obviously, for each of the 27 PAD goals included in the *PAD Goal Chart*, various further approaches exist in literature


PAD Knowledge Filter

PAD goal: Improve process organization

PA level: Function structure

Show PA representations | Show PAD principles | Show PAD methods

Principle	Goal correlation	Addressed levels				
		F	E	W	B	M
Separate different domains for parallel development	●	●	◑	○	○	◑
Separate functional chunks according to the dominant flow	●	●	○	○	○	○
Separate functional chunks according to a branching flow	●	●	○	○	○	○
Integrate design units into modules with strong interdependencies	●	●	○	○	○	●
Separate design units according to functional autonomous chunks	◑	●	○	○	○	●
Separate functions by postponing those of different configuration characteristics	◑	●	○	○	○	○
Separate functions of different configuration characteristics	◑	●	○	○	○	○
Standardize similar design units by harmonization	◔	◑	◑	◑	●	◔

Figure 6.12: Screenshot of the *knowledge filter* within the software tool

with a more specific focus. From these, further knowledge elements can be extracted and included into the knowledge base. However, since the focus of this theses is rooted in breadth aiming at a framework including as many as possible PAD goals, the depth of research is left for further works.

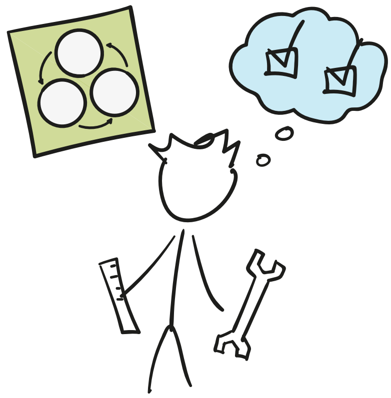
Equally, the application comfort is not in focus of the tool. The tool primary serves for illustrating the relevance of considering relations between knowledge elements what other existing approaches do not include, in most cases. Therefore, the user interface as well as the function scope of the tool is limited. In future works, for instance, the prioritization of PAD goals can be facilitated by an interactive *PAD Goal Chart*, or the tool can allow the user to model design processes according to the *Product Model Process Chart* within the tool.

6.5 Conclusion

The objective of this chapter was to elaborate and introduce a methodical approach that allows to provide PAD knowledge for designers in an appropriate way for the operative application within design situations. Therefore, on the basis of the five hypotheses on improving product architecture design, a framework has been developed comprising three constituents for recognizing PAD goals, integrating PAD into design processes, and determining the PA. These constituents can be applied within different scenarios within a design process independently of each other. However, the constituents are structured in such a way that a jointly application ensures a comprehensive consideration of the issues addressed within this thesis. In order to provide the knowledge existing in literature, the constituents of the framework integrate various knowledge elements in the form of PA representations, PA levels, PAD goals, PAD principles, and PAD methods. These can be accessed via a software tool including detailed descriptions of the knowledge elements as well as their relations allowing a cross-referencing of the elements.

The key insight of this chapter is that it is possible to describe product architecture design within an overarching framework. In this way, the central knowledge elements from existing PAD approaches can be integrated into customized PAD approaches. The framework's constituents start from a very general basis defining the goals to be addressed, the design process integrating PAD, and the actual activities to determine the product architecture. By applying the procedures proposed within the constituents, this general viewpoints on product architecture design can be specified in a way that finally very specific and individual solution approaches can be generated.

Whereas this chapter only provided a general description of the framework, the application of the framework within specific case studies, as well as a validation of its usefulness, remains open. This will be provided within the subsequent chapter.



7

Application example

Towards an initial validation of the framework

In the preceding chapter, a framework has been introduced to support designers in three scenarios: the recognition of PAD goals, the integration of PAD into design processes, and the determination of the PA. The objective of this chapter is to describe the application of the framework in order to illustrate its use in design practice and to derive first insights about the usefulness. For this, an initial validation is carried out to confirm the hypotheses formulated in Chap. 4 and to provide evidence to the usability in the three defined scenarios. Thereby, an initial answer to RQ-3 will be delivered: *How does the elaborated support improve the determination of the product architecture?* To answer this question, the chapter is structured as shown in Fig. 7.1.

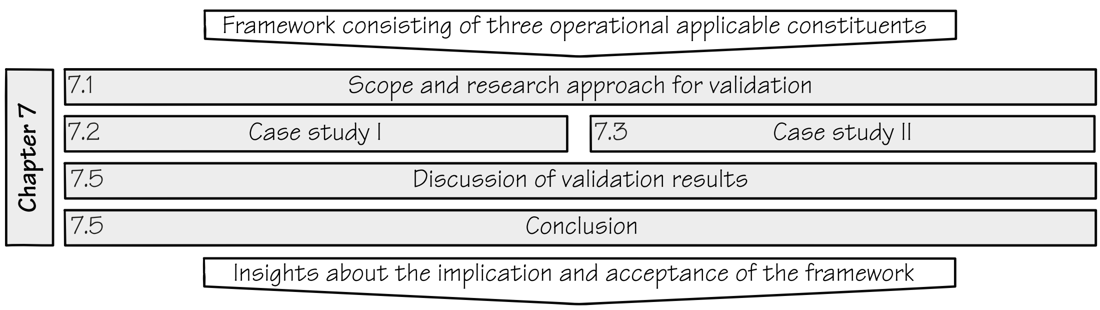


Figure 7.1: Structure of this chapter

In Sec. 7.1, the scope and research approach of the validation will be highlighted, wherein the selection of two case studies will be reasoned. The application of the framework in the case studies will be described in Sec. 7.2 and 7.3. The overall results of the case studies will be discussed in Sec. 7.4. Finally, the chapter will be concluded in Sec. 7.5.

The result of this chapter provides illustrative examples of the application of the framework in different contexts as well as initial insights about the validity of the stated hypotheses. However, this chapter does not claim to provide a final proof on the validity of the framework since the scope of the selected case studies is limited.

7.1 Scope and research approach for validation

In order to ensure a purposive implementation of the validation of the framework, this section aims at outlining the necessary steps towards proving the validity. Therefore, Sec. 7.1.1 will outline the objective of the validation, Sec. 7.1.2 will describe the research approach, and Sec. 7.1.3 will substantiate the selection of the case studies for validation.

7.1.1 Objective of the initial validation

Within the *Design Research Methodology* a *Descriptive Study* aims at evaluating a design support that has been developed before in a *Prescriptive Study*. Although the development of the support should follow a structured approach on the basis of an analysis of needs and available theories, it is a creative process based on assumptions. Therefore, it may neglect side-effects with negative influence on the envisaged situation [BC09:182]. Therefore, within the *Descriptive Study II* of this thesis, the design support shall be tested in conditions close to real industrial practice.

The basis for this validation is provided by the reference model describing the initial situation to be improved, see Sec. 3.3. Therein, three measurable success factors are defined: appropriateness of considered goals, ease in deciding on the most suitable product architecture, and appropriateness of considered product information. To improve these aspects, five influence factors were defined to be in focus of this thesis, see Sec. 3.5. For these five influence factors, five hypotheses have been postulated based on the design support that has been developed, see Chap. 4. The critical question for the validation is whether these hypotheses prove true during the application of the support, i.e., whether the influence factors are affected in a positive way.

According to the three constituents of the framework, the objective of the initial validation is to answer the following questions that are derived from the five hypotheses:

Constituent 1

- Is the overall awareness of implication of product architecture design increased (see Hypothesis 3) by applying the *PAD Goal Chart*?

Constituent 2

- Is the appropriateness of product models used within the design process increased (see Hypothesis 1) by applying the *Product Model Process Chart*?

- Is the designers' ability to allocate PAD to the most suitable points in time within the design process increased (see Hypothesis 2) by applying the *Product Model Process Chart*?

Constituent 3

- Are the accessibility and combinability of existing knowledge about PAD principles increased (see Hypothesis 4) by applying the *Basic PAD Method*?
- Are the accessibility and combinability of methods for PAD increased (see Hypothesis 5) by applying the *Basic PAD Method*?

However, the ways of how to find answers to these questions are manifold and must be chosen against the background of the limitations imposed by the environment and resources available within the context of this thesis. Therefore, an approach for validation will be discussed in the following subsection.

7.1.2 Research approach for validation

A validation of a design support can be made from various perspectives. Buur, for instance, differentiates the perspectives *logic* and *acceptance* [Buu90:3]: *Logical validity* applies when a new design theory fulfills three qualities: It is consistent regarding internal conflicts, it is complete regarding the ability to explain the phenomena envisaged, and it supports established methods as well as specific design problems. A theory is *accepted* when it is seen relevant by the scientific community and industrial practitioners. Whereas logical validity can be achieved by theoretical reasoning, acceptance can only be proved by transferring and applying the theory to new environments [Kvi10:31].

An approach for proving the logical validity of design supports ("building confidence in usefulness") is provided by Pedersen et al. [PEB+00:5ff.]. They propose a validation square as illustrated in Fig. 7.2. Therein four quadrants are shown describing different approaches for validation. The quadrants on the left refer to a validation of the support's *structure*, i.e., the internal logic. The quadrants on the right refer to the support's *performance*, i.e., the actual effects of the application. The vertical differentiation is made by the kind of studies: Theoretical studies are based on other well-accepted research whereas empirical studies are supported by tests, interviews, etc.

To achieve a comprehensive validation of a design support, all four types of validity (the quadrants) need to be considered. Thereby the types of validity base on one each other, see arrows in Fig. 7.2. Thus, a *theoretical structural validity* provides the basis for an *empirical structural validity*, and this, in turn, is required for an *empirical performance validity*. A credibility on a *theoretical performance validity* can only be achieved when the

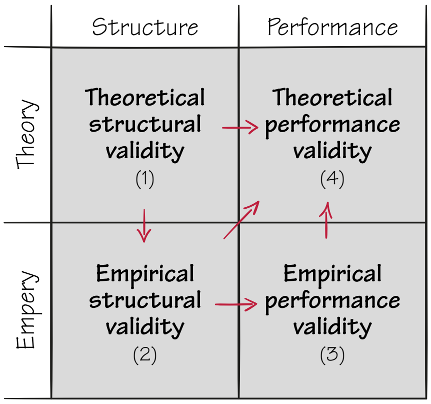


Figure 7.2: Validation square, according to [Kvi10:28] [PEB+00:6]

other three kinds of validity are proven. According to this, a four-step approach for validating a design support can be defined as described in Tab. 7.1.[9]

Table 7.1: Steps towards proving logical validity of the framework in this thesis

Step	**Objective of the step for validation**	**Consideration in this thesis**
1	Accepting the logic of the individual constructs constituting the framework (here: the hypotheses) and accepting the internal consistency of the way these are integrated	Chap. 4, Chap. 5, and Chap. 6
2	Accepting the appropriateness of the case studies (example problems) that will be used to verify the performance of the framework	Sec. 7.1.3, Sec. 7.2.1, and Sec. 7.3.1
3	Accepting that the outcome of the framework is useful with respect to the initial purpose of the chosen case studies and accepting that the achieved usefulness is linked to applying the method	Sec. 7.2 and Sec. 7.3
4	Accepting that the usefulness of the method is beyond the chosen case studies	Sec. 7.4.1

The table shows at which point within this thesis the single steps are addressed in the right column. Therefore, the first step (*theoretical structural validity*) has already been carried out within the literature-based derivation of the hypotheses in Chap. 4 and the confirmation within established approaches in Chap. 5. The consistency of the integration of the hypotheses has been demonstrated in the description of the framework in Chap. 6. The second step (*empirical structural validity*), will be considered within the preceding subsection (Sec. 7.1.3) and will be outlined specifically for each case study in detail in the following two sections (Sec. 7.2.1 and Sec. 7.3.1). The third step (*empirical performance validity*) will be described in the following two sections (Sec. 7.2 and Sec. 7.3). Thereby, the usefulness of the framework to generate helpful outputs for

[9] Pedersen et al. originally propose six steps that are aggregated to four steps for the application within this thesis [PEB+00:5ff.].

the exemplary problems is demonstrated. For the fourth step, initial conclusions will be made on the *theoretical performance validity* in Sec. 7.4.1.

By carrying out these steps, a logical validation of the framework can be achieved. However, the approach of Pedersen et al. does not include the validation of the acceptance of the framework. This can only be achieved by including potential or actual users in the validation process, for instance, by interviews or surveys [Buu90:3]. Within this thesis, this type of validation can only be described on the basis of subjective impressions of the author while demonstrating and transferring the framework to the application within industry projects and university classes. Therefore, the acceptance of the framework will only be discussed in brief in Sec. 7.4.2.

7.1.3 Selection of case studies

The approach described above highlights the importance of reasoning the selection of the case studies. Accordingly, a case study can be described as appropriate when the following three prerequisites are fulfilled:

- The case study fits the phenomenon the support is developed for.
- The problems within the case studies are problems that are intended to be addressed by the support.
- The insights/data provided by the case studies allow to draw a conclusion on the performance validity.

Regarding the first two prerequisites, various possible application scenarios can be found that fit to the phenomenon (see Sec. 4.1.2) and the problems intended to support (see Sec. 3.3). The project analysis Sec. 3.4 has provided seven examples of industry projects that were carried out during the research presented in this thesis. However, not all these projects provided the possibility to gain insights in width and depth as described within the third prerequisites. Therefore, only two validation studies have been selected that allow to validate all five hypotheses at least to some extent by the application of the three constituents. For this purpose, in some cases, the constituents had to be applied retrospectively or in an adapted way (what will be highlighted in the following clearly). Nonetheless, the case studies allow to illustrate the application for comprehensibility in this thesis and to draw first conclusions on the usefulness of the framework in examples of real problems from industry practice.

The first case study focuses on the development of platform concepts for a product family. The selection of this case study is made for two reasons: First, the challenge of coping with product variety is of a high relevance in industrial practice. Second, within the project, it has become apparent that besides variety, various other PAD goals got in focus that allowed an application of a great number of PAD principles and PAD methods. In this way, the case study provides a deeper understanding of the application of all three constituents by using the tool to access specific PAD knowledge to be applied. As a result, examples will be provided showing the usefulness of the provision of PAD knowledge to generate new product concepts regarding specific design goals.

The second case study regards the implementation of additive manufacturing technologies into design processes. Thereby, the consideration of the product architecture is of a high importance, since additive manufacturing allows, for instance, to integrate further functions into components or allows to consolidate components. In this way, the case study allows to describe the phenomenon of product architecture design within a different context compared to the first case study. This provides a basis for assessing the transferability of the framework to specific contexts of designing.

In this way, the case studies allow to illustrate the application of the framework in different contexts. As mentioned before, the focus will be laid on the logical validity of the framework. The acceptance of the framework will not be considered in the following two sections, since the framework was applied in most parts by the author. Nonetheless, insights regarding the acceptance will be concluded after the description of the case studies in Sec. 7.4.2.

7.2 Case study I: Developing a platform concept for product families

Coping with product variety is a challenge for many companies addressing individual customer needs. Within the development of air preparation units, variety is one central issue to be addressed by product architecture design. Thereby, a wide range of design goals like increasing robustness and improving process organization need to be regarded. Within this section, the application of the framework will be shown on this example from industry. Therefore, in Sec. 7.2.1, the background and objective of this case study will be described. In Sec. 7.2.2 to 7.2.4, the application of the three constituents will be illustrated by examples. Finally, the insights will be summarized in Sec. 7.2.5.

7.2.1 Background and objective of the case study

In manufacturing machines and tools used in manufacturing facilities, air driven devices such as valves, cylinders, and air motors are used in many cases. These devices require a specific quality of compressed air to be operated correctly. However, the air originating from compressors often contains unwanted solid particles, water, and oil, which can cause damages and shorten the lifetime of the air consuming devices. Therefore, air preparation units are attached upstream to the devices to ensure the demanded air quality. Regarding their (historical) main functions – filtering, regulating, and lubricating – they are also called FRL units, even if today's FRL units often realize further functions like drying, locking, distributing, or monitoring the energy consumption. Fig. 7.3 shows an example of an FRL unit consisting of four modules that are placed in series. The compressed air enters the FRL unit on the left side. Then, it passes two filter modules (first, a coarse filter, then a fine filter), a regulator module, and a lubricator module. The air leaving the FRL unit on the right side comprises the quality required for the processing of downstream applied devices.

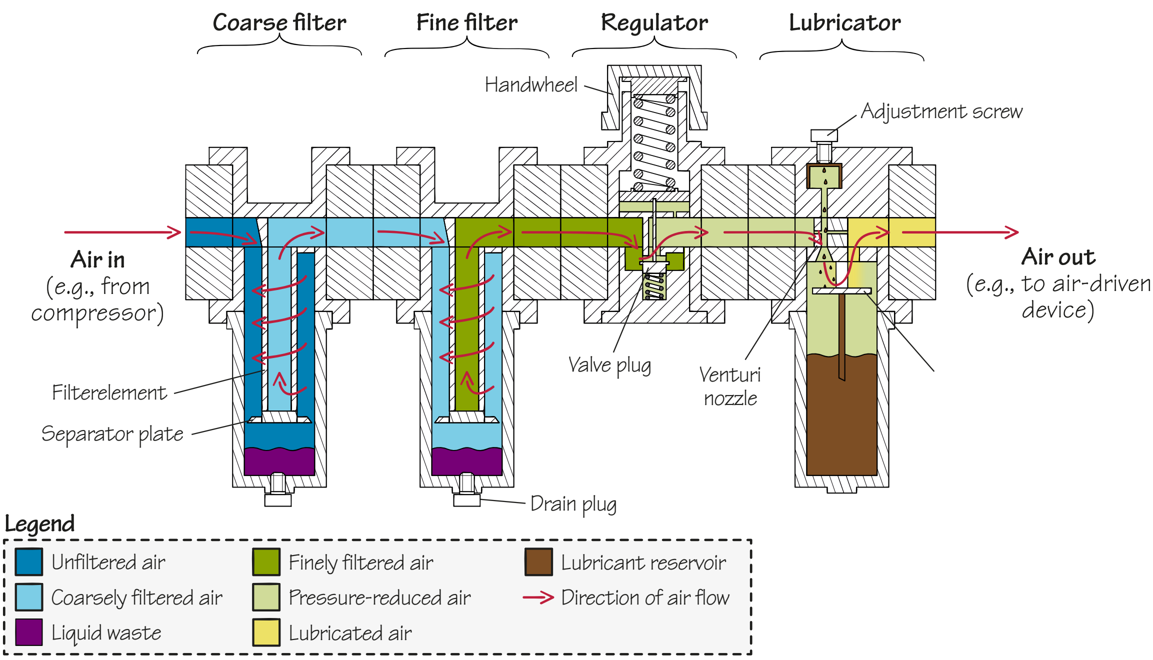


Figure 7.3: Exemplary assembly of an FRL unit

Customers of FLR units (workshop operators or plant manufacturers) demand products tailored to their specific requirements like on air quality, throughput volumes, mounting options, design, etc. Therefore, the diversity of FRL units on markets is large. Most manufacturers address the required diversity by offering modular products that allow to arrange modules in serial configuration as shown in Fig. 7.3. However, the realized modularity of the FRL-unit can entail certain disadvantages: The high number of interfaces between the modules causes extra costs for additional connection parts and results in a great effort for installation for both the producer and the customer. Furthermore, the robustness is noticeably reduced, since many interfaces exist (potential leakages) and parts stick out of the basic structure that could break off.

Due to these disadvantages, FRL unit manufacturers are considering alternative concepts to achieve an improved performance at appropriate costs for products fulfilling the individual demands of customers. Therefore, this case study deals with the development of such new concepts that were carried out in a cooperation between the Institut für Konstruktionstechnik in Braunschweig and an FRL unit manufacturer in Germany. Thereby, the application of the framework promises to be helpful, since the product architecture plays a central role in elaborating variety-oriented product concepts. During the elaboration of a platform concept, appropriate PA representations (Hypothesis 1), PAD principles (Hypothesis 4), and PAD methods (Hypothesis 5) are required to be applied. Basis for this provides a clarification of relevant PAD goals (Hypothesis 3) and an appropriate integration of PAD into the design process (Hypothesis 2). Therefore, by applying the framework, the phenomenon of product architecture design can be validated from the perspective of each hypothesis by applying each of the three constituents.

In the following, the application of the three constituents of the framework will be described consecutively. Thereby, the application of the framework is described for reasons of higher comprehensibility and clarity in a simplified way highlighting single examples of the application. However, it must be pointed out that not all constituents of the framework already existed when the project was carried out. Thus, the application of the first and second constituent was based on descriptions of PAD goals and PA levels as described in previous publications ([RIV15], [RIV16b], and [RIV16a]). Moreover, for the application of the third constituent, the tool hat not yet been developed. Therefore, the identification of PA representations and PAD principles was based on provisional Excel-based databases. However, the application of the framework could be carried out, at some points, retrospectively. Nonetheless, the case study provides a real application scenario from design practice that allows to conclude on the logical validity of the framework despite the partly retrospective application of the framework.

7.2.2 Application of constituent 1 – Recognizing PAD goals

During the development of the FRL units, various PAD goals became relevant for consideration. The focus of this subsection is to evaluate whether the strategic viewpoint provided by the *PAD Goal Chart* enables designers to gain a comprehensive understanding of implications of product architecture and allows designers to recognize those PAD goals relevant for the design project.

The definition of the general design goals was carried out at the beginning of the design project by consulting two groups of stakeholders. First, company-internal product managers were asked to define design goals and to weight them. Second, product customers of FRL units from Europe, North America, and China were asked to evaluate the importance of the design goals related to the product use from the customers' perspective in telephone interviews and an online survey. In this way, a list of design goals, which were weighted differently by the two groups of stakeholders, was identified . From the overall scope of design goals, those goals related to product architecture were of high relevance for the development of platform concepts and were discussed separately. For this, the PAD goals are plotted into the *PAD Goal Chart* in order to illustrate the allocation to strategic goals as well as to illustrate the different weightings, see Fig. 7.4. Therein, the two lines represent the independent weighting of the group of product managers and surveyed customers. The customers' weighting only includes the PAD goals within the areas *value proposition* and *customer interface* since *infrastructure management* does not concern this group of stakeholders.

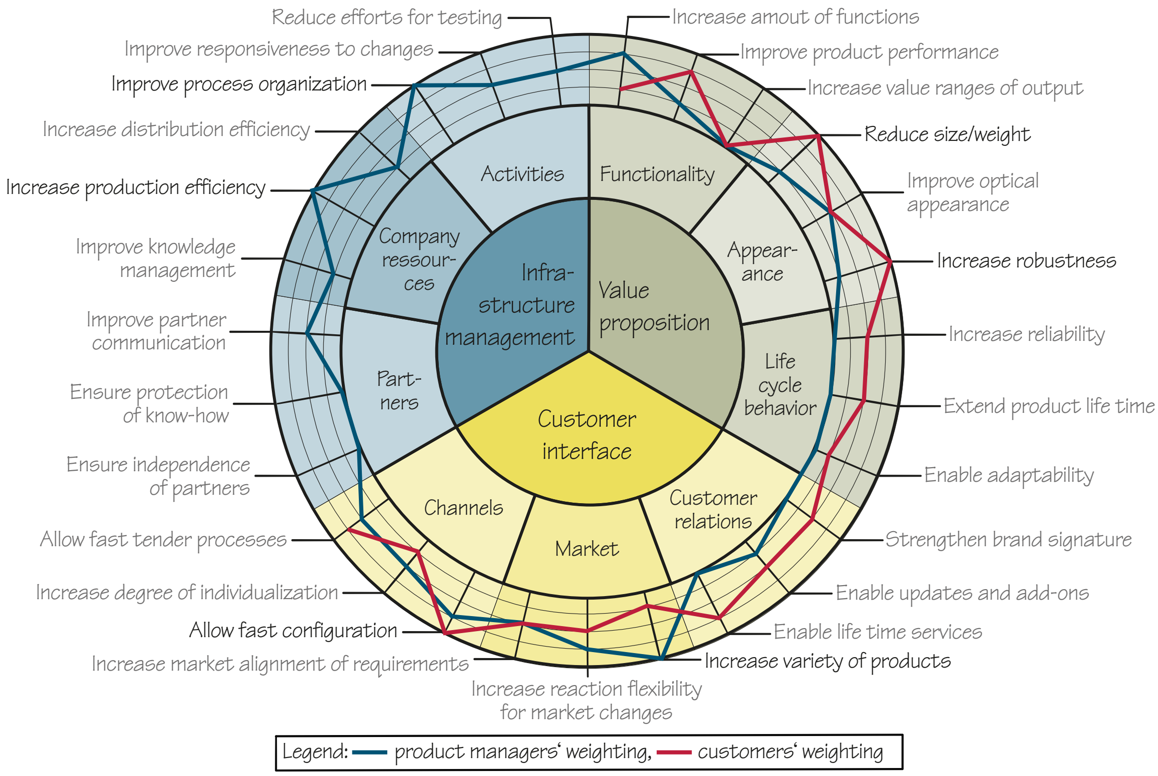


Figure 7.4: Comparision of different viewpoints on the weighting of PAD goals for the development of FRL units

In the *PAD Goal Chart*, it can be recognized that relevant PAD goals are allocated to all three strategic areas. However, the weightings differ significantly regarding single goals. For instance, *reducing size/weight* is seen as highly important for the customers group whereas the product managers rated it with a low relevance. In order to determine a clear focus of the development projects, in the most favorable case, all PAD goals with a high or very high rating of one of the two stakeholder groups can be addressed to the same extent. However, often it is not possible to do so, especially, when the goals are allocated to different strategic areas, see Sec. 4.2.3. Therefore, during the project it was decided to develop alternative concepts for different business cases – one rather focusing on the *value proposition* (e.g., *reducing size/weight, increasing robustness*) and one rather focusing on *customer interface* (e.g., *increasing the variety of products, allowing fast configuration*). For both scenarios, the *infrastructure management* (e.g., *increasing production efficiency, improving process organization*) should be considered equally. Within the PAD Goal Model, those six goals focused on in the conceptualization stage are highlighted in bold characters, see Fig. 7.4.

In this way, the application of the *PAD Goal Chart* illustrates the necessity of a comprehensive clarification of PAD goals since different goals can be relevant to product architecture design. For this, the chart allows to overview different PAD goals relevant to the design task and prevents a fixation on single goals like *increasing the variety of products* or *increasing robustness.* The representation of the results within the radar chart enables to easily compare different results and facilitates the discussion between different stakeholders – for weighting of design goals as well as for opposing ratings of product concepts regarding the defined goals (not shown in the figure). Moreover, the allocation of the design goals to the strategic fields supports companies in discussing different scenarios for business cases of products as they shall be further discussed in this case study.

7.2.3 Application of constituent 2 – Integrating PAD into the design process

The results of the application of the first constituent provide the basis for designers to determine product concepts according to appropriate design goals. The application of the second constituent aims at allowing them to understand at which stages in the design process these goals can be addressed. By applying the *Product Model Process Chart,* it shall be shown that in the design process different basic PA levels are passed that can provide a suitable basis for addressing PAD goals.

As mentioned before, the application of the framework is made partly retrospective to the design project. Therefore, the *Product Model Process Chart* is used to model the actually carried out design process subsequent to the project. In this way, it can be illustrated how the intuitively defined design process was appropriate to address the relevant PAD goals. Nonetheless, the retrospective analysis can provide indications for the usefulness of the *Product Model Process Chart* for defining a design process appropriate for this real case.

Thus, the design process carried out in the project mainly consisted of five phases of that each was consisting of several stages, see Fig. 7.5. Generally, the process was similar to the process of Pahl et al. as described in Sec. 2.2.2. Therefore, the first phase aimed at clarifying the design goals based on company-internal sources as well as interviews with customers (results are presented in the preceding subsection). Within the second stage, initial product concepts were elaborated focusing on the definition of functions and modules in order to elaborate platform concepts to be evaluated against possible business cases. Thereafter, the third phase aimed at refining the requirements on the product based on the business case chosen. Then, the detailed design is carried out in the fourth phase passing through all basic PA levels by refining function structures, elaborating alternatives for effects and working principles within a morphological box, and determining the embodiment by defining the building structure and module structure considering all life phases. After these phases, a further level of detail should be attained by passing through the design states of the layout and the full description. However, this was not part of the project focusing on conceptualization.

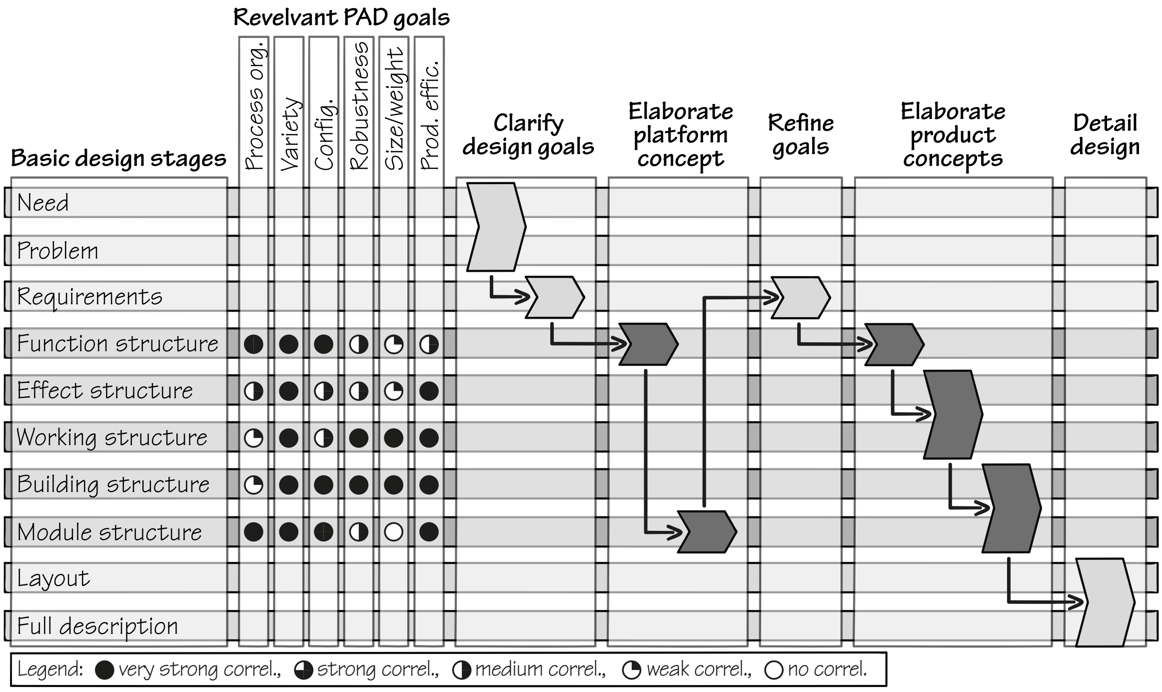


Figure 7.5: Application of the *Product Model Process Chart* to integrate PAD into the design process

The representation of the design process within the *Product Model Process Chart* allows to identify at which stages the product architecture can be determined in order to address the defined PAD goals or how the process needs to be changed in order to allow so. Therefore, for each defined PAD goal, it has to be regarded which product models are suitable for their consideration. Therefore, the knowledge base of the framework allows to identify the basic PA levels most suitable for addressing the six PAD goals as defined within the first constituent (for screenshot of the *PAD Goals/Levels Chart* in tool see Fig. F.1). For instance, it can be identified that the PAD goal *improving process organization* (G25) as well as *allowing fast configuration* (G16) and *increasing the variety of products* (G13) can be addressed primarily on the level of the function structure and the module structure. Since these goals are considered as highly important to define first platform concepts, they are mainly dealt with in the stages of the second phase. By considering the working structure and the building structure in detail, the other PAD goals can be addressed what is part of the fourth phase.

In this way, the *Product Model Process Chart* serves to translate PAD goals into PAD stages within the design process. In this way, appropriate integrating points for the third constituent are defined. Within this application example, it can be shown that different PAD goals require a consideration on different PA levels. Therefore, it is highlighted that PAD is not suitable to be integrated at only one stage within the design process. Rather, it was shown that some goals can mainly be addressed by only considering the function structure as well as the module structure. This serves for defining a platform concept (here in the second phase) that can be further detailed by considering all relevant PAD goals within the next stages when all basic PA levels are passed through. The determination of the product architecture according to this design process will be described by support of the third constituent.

7.2.4 Application of constituent 3 – Determining the product architecture

The before defined stages provide the basis for the determination of the product architecture. Therefore, the *Basic PAD Method* can be applied in each of the stages to guide the designers in clarifying the PAD goals, generating PA representations, analyzing and synthesizing the PA, and evaluating concepts, see Fig. 6.6. This subsection aims at illustrating examples of how the method is executed and how knowledge elements are identified within the software tool and applied to specific contexts.

Since the *Basic PAD Method* is repeatedly and iteratively applied many times during the design process, here, only single examples of the application will be shown. The chosen examples constitute decisive stages in the design process and demonstrate applications of the procedure of the Basic PAD Method. These chosen stages are highlighted on the left hand-side of Fig. 7.6 (compare with Fig. 7.5). Therefore, the first example comprises the consideration of the function structure while the following two examples comprise the module structure and the working structure.

For the first stage, on the right hand-side of Fig. 7.6 the steps of the *Basic PAD Method* are outlined. For each step, examples of specific knowledge elements are named that

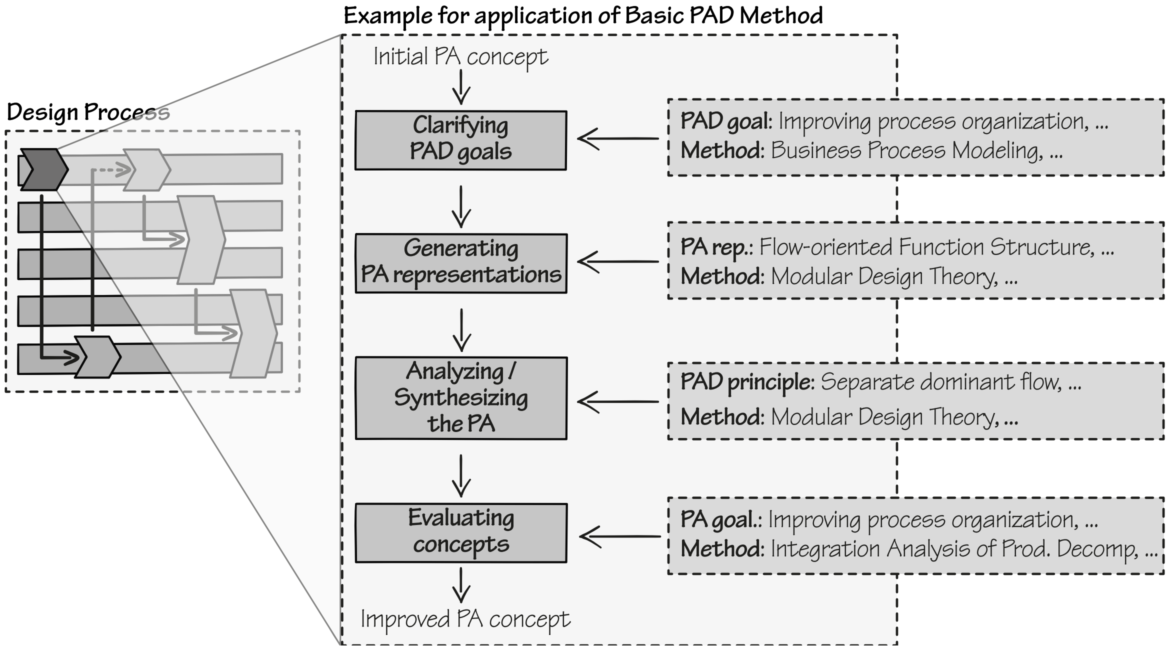


Figure 7.6: *Basic PAD Method* as applied within the stage of the design process considering the function structure of the product

can be identified in the knowledge base. For this, the tool allows to filter the database, see Fig. F.2 to F.6. In the following, each step will be described in short.

1. **Clarifying PAD goals**: The PAD goals considered in this stage are *improving process organization* (G25), *increasing the variety of products* (G13), and *allowing fast configuration* (G16). For the clarification of the goals, further information has to be gathered, for instance, which organization units are included in the value-creating process. Methods can support the clarification of the goals if required. In this case, for instance, the method *Business Process Modeling* by Vietor et al. (M2) can support the identification of roles of organization units like development team in the process. The *Generation of a Variety Tree* Kipp (M14) can be elaborated illustrating which variants of the products are required and how these are configured.
2. **Generating PA representations**: The function structure can be represented in various ways. Specific for the chosen goals, a *Flow-oriented Function Structure* by Stone et al. (R4), a *Product Family Function Structure* by Blees (R13), or a *Domain-oriented Function Structure* by Jansen (R3) can be appropriate. Since in this case, all these perspectives seem to be valuable, a combination of these function structures will be generated. Thereby, the corresponding PAD methods proposed by the authors include guidelines for the generation of the representations.
3. **Analyzing and synthesizing the PA**: On the basis of this representations, in the third step, the PAD principles can be identified like *separate functional chunks according to the dominant flow* (P39). A complete list of principles will be described in detail later.

Generally, the principles' descriptions within the database are sufficient for applying the method. Additionally, the method's descriptions within the original sources can be acquired like the *Modular Design Theory* of Stone et al. (M13).

4. **Evaluating concepts**: Finally, the evaluation of the developed concepts regarding the defined PAD goals is carried out. Methods can support this evaluation, for instance, by determining key performance indicators (KPIs). For instance, for the goals *improving process organization* (G25), the method *Integration Analysis of Product Decomposition* of Pimmler and Eppinger (M10) can be applied to quantify the dependencies between functional chunks of the product.

To illustrate the application of the steps, the focus shall be laid on the application of PA representations and PAD principles. Thus, Fig. 7.7 shows a simplified section of the function structure created for the FRL unit. It shows the functions of one module for filtering and one module for regulating, compare Fig. 7.3. This specific function structure combines elements of the PA representations mentioned before. Thus, the basis provides the illustration of functions like *introduce air flow*, *swirl flow*, and *filter air flow*. Between the functions, the flows of energy, information, and material are described. Hereby, the compressed air flow is considered as energy, since this is its main role within pneumatic systems. Additionally, the variant functions are highlighted by stacked function labels. For instance, the function *filter air flow* is variant, since different fineness of the filter is required for different use cases. Moreover, the domains are coded by colors. In the case of the FRL unit, the company differentiates between departments for filter technology and regulator technology that shall develop and test the related functions.

The PAD principles, which are identified within the tool, are listed in Tab. 7.2. For each principle, it has to be decided if it is applicable in the specific case. The result of the application of some principles is shown in Fig. 7.7. To illustrate one example, the principle of *dominant flow* (P39) shall be described in brief. The principle aims at separating flows that pass the system from the entry to exit. For the FRL unit, this is the case for the air flow. Therefore, the functions from *introduce air flow* until *pass on air flow* are regarded as a separated set of functions that should be considered within the development process as one unit. However, other principles, like the *domains* (P36) and *configuration* (P41) require a further separation of the dominant flow. In this way, the functions *swirl air flow* and *filter air flow*, as well as *dispense air flow* have to be considered separately due to their allocation to specific domains.

Thus, by considering the function structure, a solution-neutral description of the product is generated that includes clusters of functions to be considered separately.

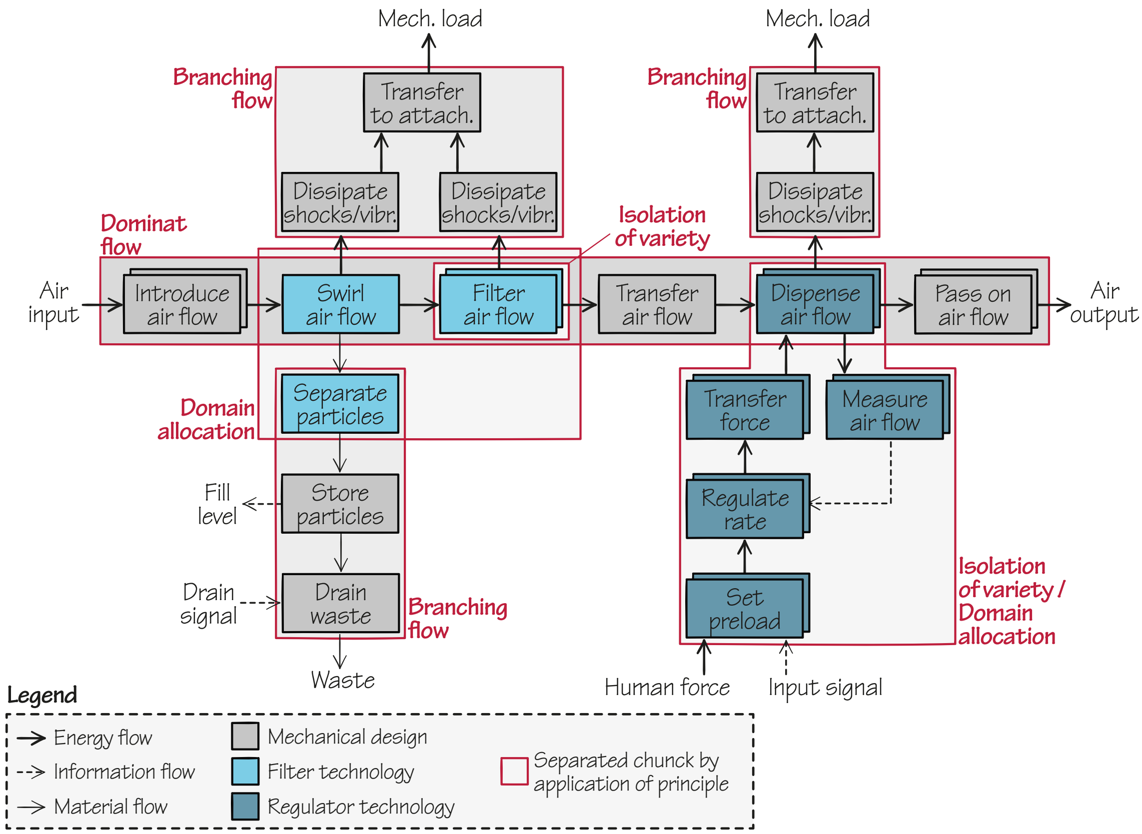


Figure 7.7: Function structure of the FRL unit

Table 7.2: Examples of PAD principles proposed to be applied to the function structure for achieving the goals *process organization* (G25), *variety* (G13), and *configuration* (G16), compare Fig. F.3

PAD principle	Application in example
P39: Separate functional chunks according to the **dominant flow**	The main flow is constituted by the air flow. As possible, the corresponding functions shall not be considered as dominant within the design process.
P36: Separate different **domains** for parallel development	Filter technology and regulator technology are allocated to special department and shall be developed separated from the rest of the product.
P38: Separate functional chunks according to a **branching flow**	Branching flows are constituted by the drain of waste and the signal input of the regulator that can be considered separately.
P41: Separate functions of different **configuration** characteristics	The filter function (variant fineness) as well as all functions related to the air flow regulation (variant accuracy) are variant and shall be separated to allow configurability.
P9: Integrate design units into modules with strong **interdependencies**	No need identified since complexity of the function structure is low. Effort for application (required generation of DSM) not considered as worthwhile.

The next step of the design process, see Fig. 7.5, aims at developing a preliminary module structure of the product that allows to address the same PAD goals as in the function structure. Therefore, the module structure shall allow to describe a structure of the product family that permits to configure variants, but also to consider the organization structure of the company. PA representations of the module structure focusing on these goals are, for instance, provided by the *Organ Diagram* of Harlou (R5) and the *Module Interface Graph* after Blees (R10). Both focus on a representation of modules by distinguishing *standard* and *variant* modules. According to these, in Fig. 7.6, two alternative module structures of the FRL unit are shown. The standard parts (light grey) are distinguished by their ability to be used in different configurations like the housing in the first concept. The platform (dark grey) are used as the basis for the whole product family in the first concept. Moreover, some parts are used as standard part within specific modules like the swirler that is used in coarse filters as well as in fine filters (yellow). Other parts are variant like the filter elements or the regulator (green).

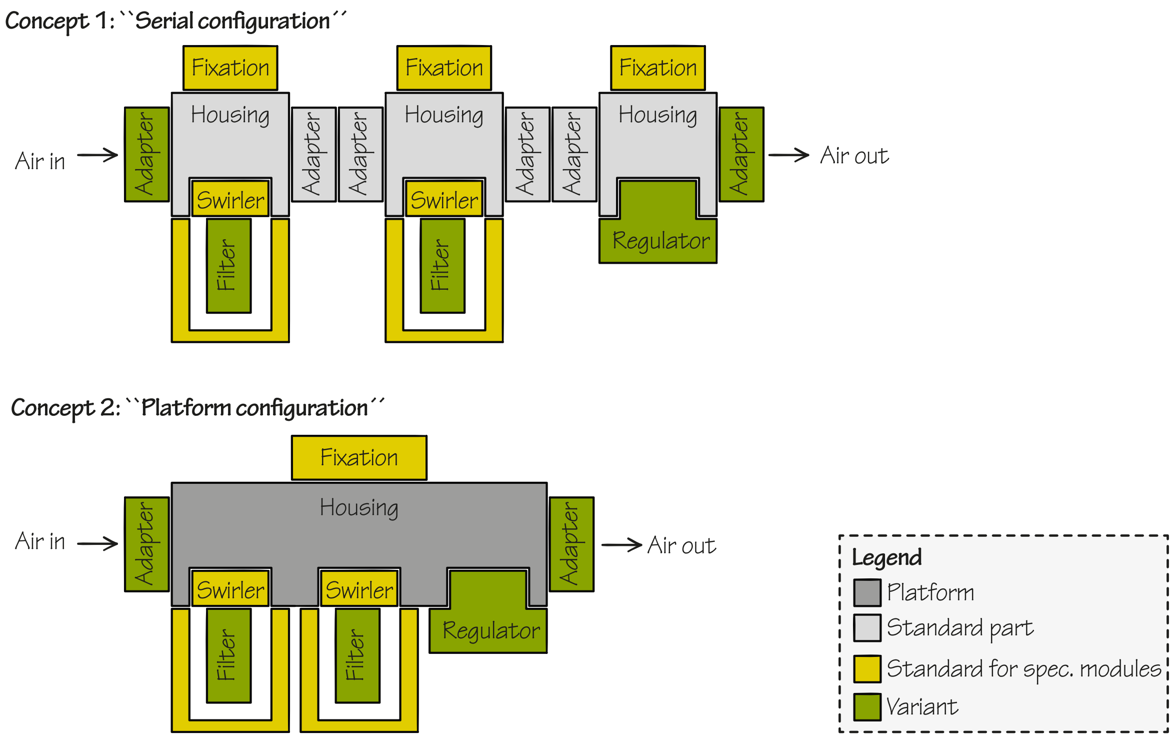


Figure 7.8: Alternative concepts of the module structure of the FRL unit

The principles that the two illustrated concepts of the module structure are based on are listed in Tab. 7.3. It can be recognized that some principles provide mutually exclusive solutions. For instance, *serial configuration* (P57) and *platforms* (P15) are not compatible in this case. Therefore, designers have to evaluate the concepts against each other. For the FRL unit, both alternative concepts have advantages. The serial concept allows to configure a greater variety of FRL units, for instance, by combining different types of filters in a row (from coarse to fine). The platform concept promises to increase the robustness of the product and decreases the effort for assembly. In contrary stand the reduced possibilities to configure different variants since the number of main functions is not variable. In the case of the industry projects considered here, both concepts were further developed. As described in Sec. 7.2.2, the concepts can address different business cases. While the platform concept is rather appropriate for a *value proposition* scenario, the serial concept has advantages in a *customer interface* scenario.

Table 7.3: Examples of PAD principles proposed to be applied on the module structure for achieving the goals *process organization* (G25), *variety* (G13), and *configuration* (G16), compare Fig. F.5

PAD principle	Application in example
P57: Variate products by **serial configuration** of modules	Applied to the concept "'serial configuration"' where the main functions *filtering* and *regulating* (and others) can be cascaded in any order and number.
P56: Variate products by **sectional configuration** of modules	Applied to the concept "'serial configuration"' where adapters that can be placed at any modules at entry or exit.
P17: Separate design units according to **demanded configurability**	Modules for *filtering* and *regulating* are separated modules that can be interchanged in the concept "'serial configuration"'.
P15: Integrate standard modules into a **platform**	Applied to the concept "'platform configuration"' where components that are not variant are integrated for increasing robustness, size, etc.
P28: Separate design units for allowing **pre-assembly**	Achieved by using a platform in the concept "'platform configuration"'.
P9: Integrate design units into modules with strong **interdependencies**	Not applied, see F5 in Tab. 7.2.

In the preceding stages, these concepts are further detailed by a consideration of each PA level. Thereby, within each stage, different PA representations can be generated and different PAD principles can be applied for addressing all defined PAD goals. One example of a principle's application focusing on *increasing product efficiency* (G23), *reducing size/weight* (G4) and *increasing robustness* (G6) is illustrated in Fig. 7.9. Therein, on the left hand-side, a sectional drawing of the filter unit and parts of a neighboring unit are illustrated, compare Fig. 7.3. The solution as shown in the figure is derived from predecessor products that shall be redesigned. The considered component is an adapter that is part of each of the modules of the FRL unit on the input side as well as on the output side. The adapter includes a thread that allows it to connect air pipes to the FRL unit. Obviously, this is only required when the module is one of the outer modules of the FRL unit. Additionally, the component fulfills the function of fixating an O-ring that is used to seal modules against each other. This is only required between inner intersections between modules. Therefore, the components fulfill two functions of that only one is required depending on the installation position of the module.

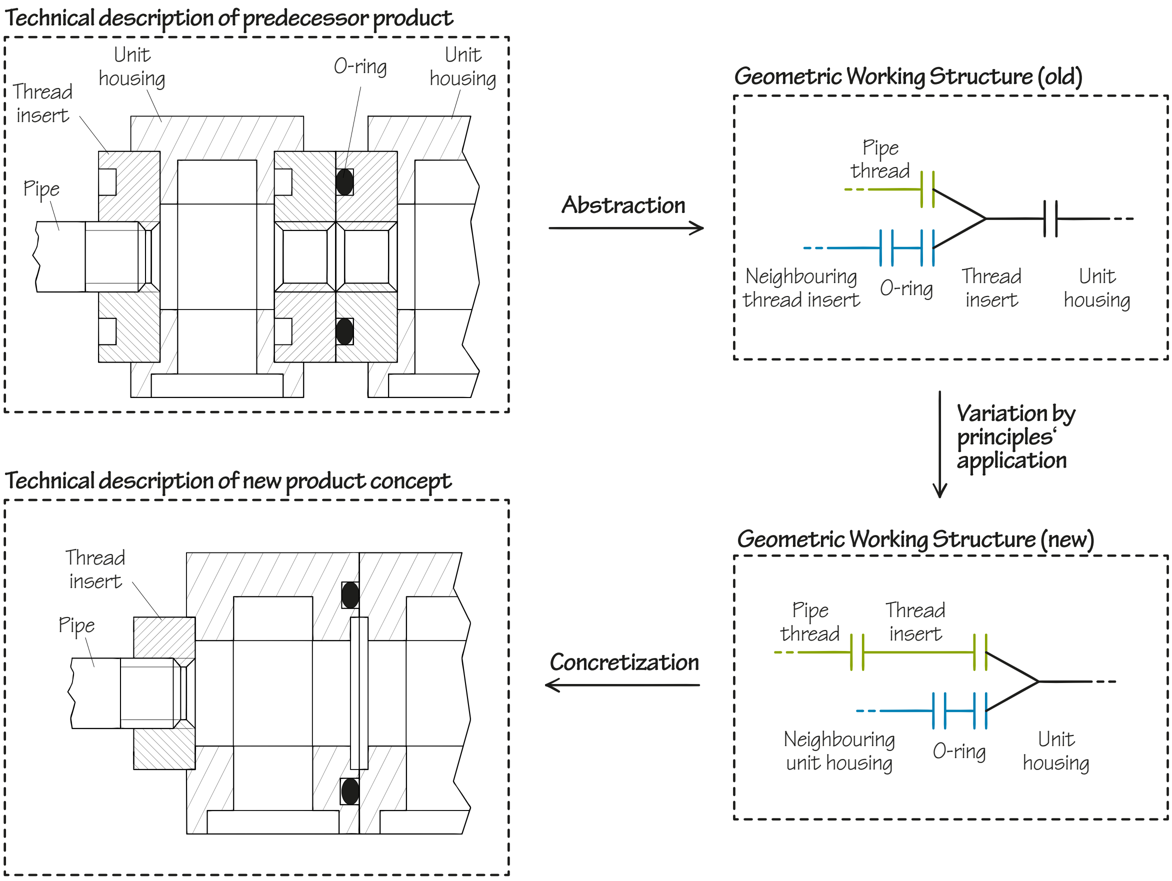


Figure 7.9: Example of applying a principle on the working structure of the thread inserts of an FRL unit

However, since the product costs, the required building space, and the weight of the adapter are high due to mechanical requirements that necessitate a product of metal, the component is in focus of the application of PAD principles. In order to analyze the product architecture of the section, a *Geometric (Working) Structure* according to Roth (R6) is generated. The result of this abstraction of a cutout of the FRL unit shows the upper part of Fig. 7.9. It shows that the thread insert has three working surfaces of that two are paired with other working bodies that are only optionally neighboring the component (colored in green and blue). Thus, in the case, the module is mounted at the outside (e.g., air in) of the FRL unit, the thread insert is connected to the pipe thread (green). In the case, the module is connected to another module, the thread insert does not accommodate a pipe thread, but seals the gap between the the modules with an o-ring (blue).

On this kind of PA representation, several PAD principles can be applied. Three of the principles are listed in Tab. 7.4. For instance, the principle *separate design units by differentiation standard and variant sections* (P25) allows to separate the thread insert. Thus, the bottom part of Fig. 7.9 shows a variation of the thread insert. The thread insert of the new concept only includes two working surfaces and is only required for connecting the air pipe to the FRL unit. Therefore, it is required to be mounted to those module sides at the outside of the FRL unit, but not when two modules are connected. This is allowed by shifting the function of fixating the O-ring to the housing of the FRL unit. In this way, various principles can be applied for improving the FRL unit regarding the defined PAD goals.

Table 7.4: Examples of PAD principles proposed to be applied on the working structure for achieving the goals *size/weight* (G4), *robustness* (G6), and *production efficiency* (G23), compare Fig. F.6

PAD principle	Application in example
P25: Separate design units by **differentiating standard and variant** sections	Applied to the adapter that includes working surfaces only required for specific configurations (outer position of FRL unit or inner position).
P50: Standardize similar design units by **harmonization**	The adapters are harmonized by excluding the groove for mounting the o-ring.
P3: Integrate design units by **increasing the number of working surfaces**	The groove for mounting the o-ring is integrated into the housing.

Even though only single examples of the application of the third constituent have been shown, it was illustrated how the *Basic PAD Method* provides a generic procedure that allows to elaborate and evaluate concepts of FRL units. Especially, the provision of PAD principles allows to make use of knowledge for generating new ideas to improve the products regarding specific PAD goals. Specific PAD methods allow to supplement procedural knowledge for clarifying the goals, generating PA representations, and evaluation.

7.2.5 Conclusion

This case study aimed at demonstrating the application of the framework for product architecture design in order to draw conclusions on the usability of the framework. The application was shown on single examples comprising the use of all three constituents. In this way, it was shown how the design project could be supported from the recognition of PAD goals to the integration of PAD into design processes until the determination of concepts for the product architecture on different PA levels.

For the design task of this case study, the application of the framework turned out to be useful since a variety of PAD goals was identified as relevant to the development of FRL unit. The first constituent allowed to overview this variety of PAD goals and determine business cases oriented at the strategic design goals corresponding to the PAD goals most important. The second constituent, even though it had been applied retrospectively, allowed to illustrate that PAD needs to be integrated at different stages of the design process. Finally, various examples of principles were applied in different PA levels that highlighted the usefulness of the third constituent to allow designers to access specific prescriptive knowledge. In this way, they were supported to determine the product architecture according to the defined PAD goals.

7.3 Case study II: Exploitation of potentials of additive manufacturing

The implementation of emerging manufacturing technologies like additive manufacturing (AM) into design processes offers various potentials to improve products and processes. Many of these potentials are closely linked to alternative concepts of the product architecture that are enabled by the specific manufacturing capabilities of AM. Therefore, the second case study aims at transferring the presented framework to the general challenge of enabling companies in the automotive sector to integrate the consideration of AM into established design processes. To precise this motivation, in Sec. 7.3.1 the background and objective of this case study will be outlined, before in Sec. 7.3.2 to 7.3.4 the transfer of the three constituents into established design processes will be described. The results will be summarized in Sec. 7.3.5.

7.3.1 Background and objective of the case study

In the last years, AM has gained a growing importance as a serious additional option to conventional manufacturing technologies – also for products in series production. While potentials like tool-less manufacturing were in earlier days especially applied in prototyping ("rapid prototyping"), nowadays they are also applied to the manufacturing of end-products (at least for smaller series) to reduce tooling costs, and shorten development and production time. Moreover, the realization of new design features is made possible, for instance, due to the design of complicated geometries (neglecting constraints of conventional technologies like draft angles or overhangs), or the realization of graded materials, cf. [GRS15:404ff.] [Kum18:80ff.]. Many of these capabilities are closely linked to the consideration of the product architecture since in many cases not only single elements of a product but the structure of these is in focus [BRC+13:2] [LSD+16:280]. For instance, the capability of manufacturing complicated geometries makes the integration of components possible that had to be manufactured separately relying on conventional technologies. Therefore, PAD principles can provide an inspiration for designers to review the product architecture of existing products and to elaborate new concepts that can be realized best by AM.

However, the challenge for traditional industries like the automotive sector is to enable designers to consider AM at the most suitable stages of the design process to make best use of its capabilities, cf. [SRV17:132ff.]. Even though various methodical approaches for providing the required knowledge about AM are known (*Design for AM*, short: *DfAM*), these approaches often only provide insufficient support for the systematic analysis of existing products in order to identify potentials to implement AM. Mostly, the approaches provide information about potentials of AM ("opportunistic" approaches) or on the restrictions of AM ("restrictive" approaches), but do not provide methods applicable within established design processes to facilitate the recognition of AM as an alternative at all [Kum18:42ff.]. Therefore, there is a lack of an approach that allows analyzing the different types of product models being used in established processes in order to enable designers to apply AM knowledge at the most appropriate stages of the design process, cf. [RSW+17:6ff.].

Accompanying the research presented in this thesis, a research project with an automotive manufacturer was initiated to elaborate such a comprehensive approach for the implementation of AM knowledge into the design process. Since the project aimed especially at the exploitation of AM potentials in conceptualization, the key ideas of the framework presented within this thesis were taken as a basis for the new approach. For the validation of the hypotheses, the case study allows to consider all five subphenomena of product architecture design. Thus, both the definition of appropriate product models (Hypothesis 1) as well as the integration into the design process (Hypothesis 2) have been proven to be of high relevance to the implementation of AM. Thereby, the recognition of potentials of AM can be supported by similar approaches to the recognition of PAD goals (Hypothesis 3). This allows to access the most appropriate AM principles based on PAD principles to address these goals (Hypothesis 4). Finally, to implement these AM principles, the *Basic PAD Method* can provide an appropriate basic structure of ideation workshops to be carried out with designers (Hypothesis 5). Considering this, the application of the framework within the context of DfAM allows to draw conclusions on the appropriateness and transferability of the framework to specific design situations.

7.3.2 Application of constituent 1 – Recognizing PAD goals

Due to the shifted focus of this case study, the main goal of the application of the first constituent to the context of DfAM is not to recognize PAD goals but to recognize potentials of AM. Therefore, the *PAD Goal Chart* can only be applied with limitations since only that goals are relevant that can actually be achieved by the integration of AM (in the following: *AM goals*). However, with the same reason as it has been introduced for PAD goals, also for AM goals it is suitable to classify the goals according to strategic goals of the company. Equally, as PAD goals, AM goals can address various business sectors of the company. Therefore, within this thesis, the *PAD Goal Chart* is described for ensuring traceability of the approach for the reader. This allows to draw direct connections to PAD principles that will be applied within the third constituent since the goals included in the *PAD Goal Chart* cover all PA goals relevant in this case study. Nonetheless, within the industry projects, actually, a goal model specific to AM was used as described in further publications, see [RSW+17:9f.]. Extensive works within this context are presented, for instance, in [WKV16:3ff.] [Kum18:80ff.].

Thus, Fig. 7.10 shows the *PAD Goal Chart* in which those goals are greyed out that cannot be addressed by AM. Nevertheless, the potentials of AM refer to goals in all strategic areas. For instance, *value proposition* can be increased by reducing the product's weight (e.g., by integral designs enabled by manufacturing complicated geometries), *customer interface* can be enhanced by offering high individualized products (e.g., by cost-efficient one-piece manufacturing), and *infrastructure management* can profit of reduced manufacturing costs (e.g., by the omission of costs for tools like casting molds). The plotted graph within the chart represents one possibility of how the chart can be used to weight the relevance of these goals for the analysis of a specific component for that AM is considered as manufacturing technology. The graph here is the result of the application to a component called *air breather*, which will be further described in Sec. 7.3.4. The goals most relevant to this components are highlighted in bold characters.

The purpose of this representation is to enable designers to recognize potentials that are often overseen. In the workshops carried out, it has been shown that designers often only focus on goals that have a direct effect on their personal work. These are, in many cases, design goals affecting the design process in *infrastructure management*, for instance, the *process organization*, the *responsiveness to changes*, or the *production efficiency*. In contrast, *value proposition* and *customer interface* is only of secondary importance for designers since in most cases predecessor products exist that already fulfill the requirements. Consequently, in new development projects, only incremental changes

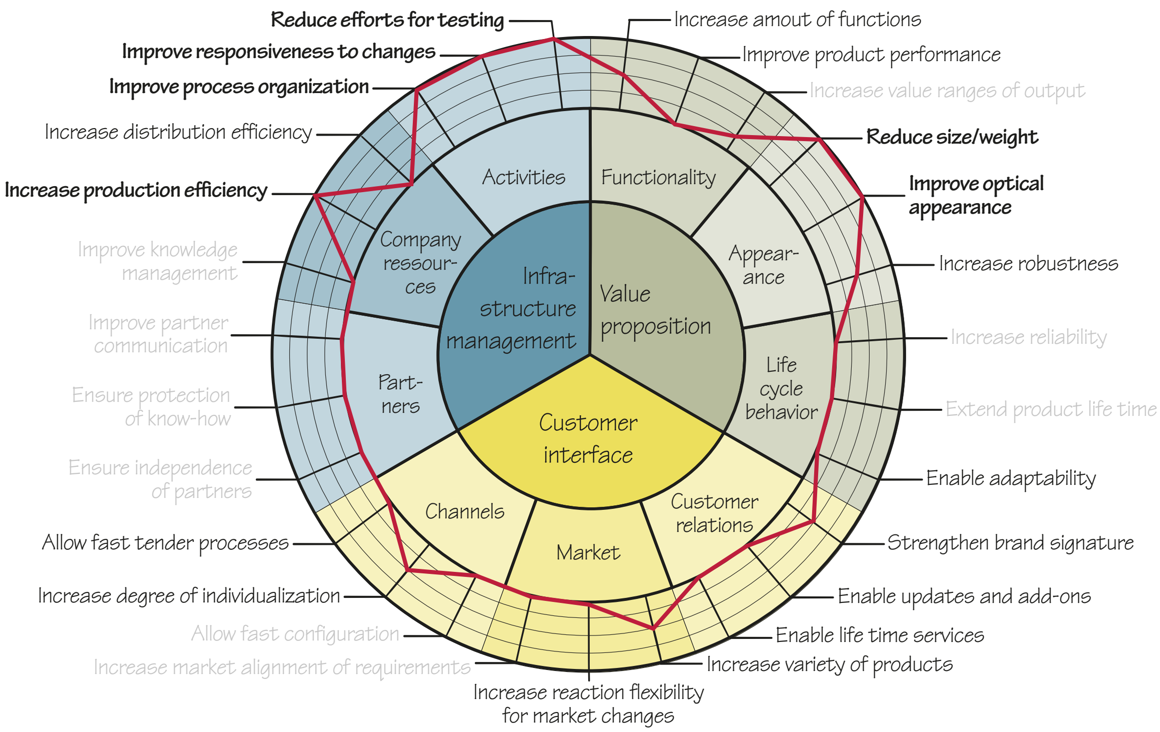


Figure 7.10: Spectrum of PAD goals that can be addressed by the implementation of AM

compared to the predecessor products are made, for instance, by adapting the geometry to new constraints of space. Moreover, often it is not even regarded whether, for instance, fundamental weight reductions through the consolidation of components can be achieved. For the recognition of potentials like these, designers are missing the incentives. Therefore, the goal model can provide a first step towards a more comprehensive and critical analysis of potentials of AM. However, the organization of the whole design process needs to allow designers to uncover innovations. In the normal processes, these are left to the very early stages of the design process, but not the stages when experts of manufacturing technologies are integrated into the development.

In conclusion, the general concept of the *PAD Goal Chart* provided an increased understanding of the potentials of AM and allowed designers to recognize issues that they do not have in mind in everyday work. Based on the definition of goals most relevant to specific components, the goal chart can be used as a starting point for engaging designers to consider AM as an alternative manufacturing technology. Its implements into the design process then can be supported by the second and third constituent of the framework.

7.3.3 Application of constituent 2 – Integrating PAD into the design process

As described in Sec. 7.3.1, the consideration of the implementation of AM into design processes is often made on the basis of non-suitable product models. The application of the second constituent shall allow to elaborate a deeper understanding of the use of product models within the design process in order to integrate the consideration of AM appropriately. Thereby, basic PA levels shall provide the basis for describing established design processes in the automotive industry to the identification of suitable points in time to integrate the consideration of AM.

Therefore, within a first step, the design process of the automotive manufacturer has been analyzed. Within this thesis a simplified reference process leaned from [GS16:278] provides the basis for the explanation of the application of the *Product Model Process Chart*. Therefore, generally, an automotive design process comprises four phases. These are *goal definition*, *conceptualization*, *series development*, and *series launch*. Within the chart in Fig. 7.11, the product models used in the phases are illustrated.

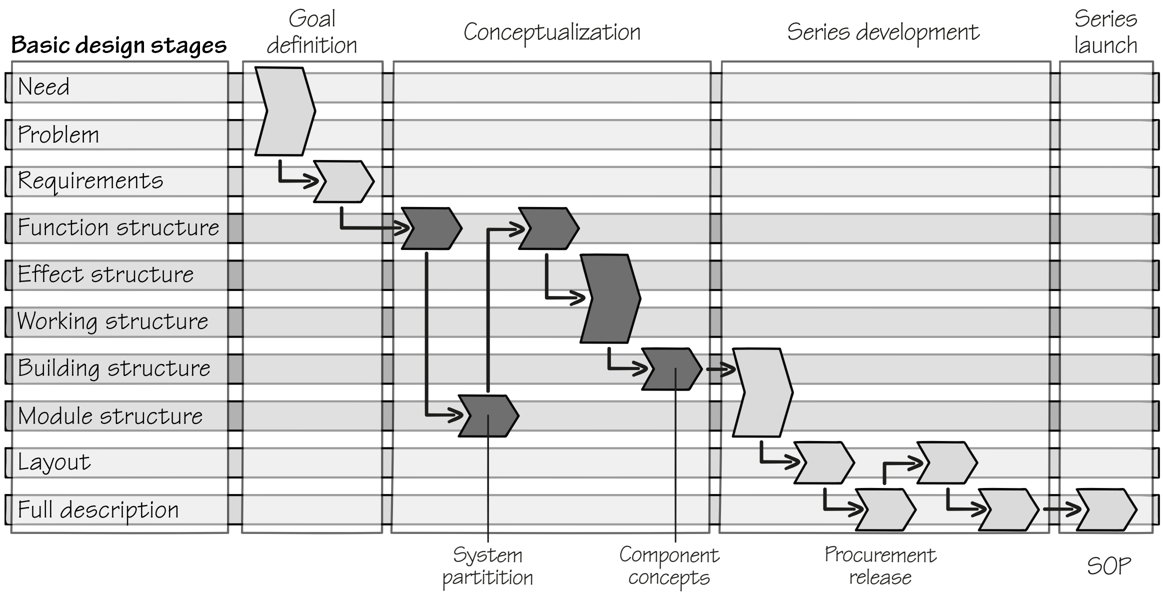


Figure 7.11: Reference process within the automotive industry

In the first phase of *goal definition*, the whole product system (the automobile) is planned by defining the customers' needs, the addressed problems, and the requirements on the sub-systems. Thereafter, in the *conceptualization* phase, the system is partitioned by defining functions and allocating these to modules of the product. After this, the modules are conceptualized by refining function definitions and regarding effects, working principles, and first drafts of the building structure of the product. In the third phase of *series development*, the building structure and the module structure is refined considering, in particular, production processes. Then, the layout of the components is completed resulting in the design freeze. A further level of detail is achieved for the procurement release, allowing to define supplier for the production of components. Depending on the decision of a supplier and the specific manufacturing restrictions, minor adaptions of the components' layout are made. After the product release, the *series launch* paves the way to the start of production (SOP) by adding further detail to the product description.

Modeling the process within the *Product Model Process Chart* allows to understand in which stage which level of product models are considered. To integrate the implementation of AM into the process, it must be regarded which product models are suitable to exploit the potentials of AM. Similar to the argumentation regarding product architecture design, also for AM it can be stated that the same levels from function structure to module structure are important for consideration. The reason for this is, that AM capabilities can be applied on all levels. For instance, for integrating additional functionality enabled by AM to a product, the function structure has to be considered. Moreover, AM allows to realize alternative effects (like 4D printing), or new working structures (like graded materials). On the components structure, components consolidations can be identified, while the module level allows to innovate assembly processes (by insertion of components during the printing process) or service (by rapid repair). For further explanation of examples on all five levels see, [RWI+16] and [RSW+17].

Within the automotive design process as shown in Fig. 7.11, it was examined by retrospective analyzes of projects that, in most cases, AM is considered at first in series development after the procurement release. Especially, in cases when costs for producing tools, for instance, for die casting or injection molding exceed the costs of additively manufactured parts, the decision had been made for AM. Thus, the design process allowed only to marginally adapt layouts of the components to comply with the requirements of the chosen manufacturing technology. In this way, the component that would have been manufactured conventionally is substituted by a component manufactured additively. However, AM provides numerous more potentials than faster and cost-efficient production for small series. Though, the exploitation of these potentials requires in many cases a revision of the product architecture that can only be achieved by manipulating the regarding product models, cf. [SRV17].

Therefore, the target identified by the *Product Model Process Chart* is to consider AM earlier within the design process, best, when first considerations about the product architecture are made, i.e., during conceptualization. For achieving this, a strategy including various actions has been defined within the project. First, generally, designers involved in all stages shall be trained regarding the potentials of AM in order to allow them to consider these at each stage, cf. [WKV16]. Second, at the beginning of the system partition stage, a screening of all functions and predefined sub-systems shall be made by AM experts to identify promising parts for that AM shall be considered separately, cf. [SRV17]. And third, during the design process, workshops shall be carried out for analyzing potentials of AM for specific sub-systems in an interdisciplinary team, cf. [RWS+18]. In the following, a concept for carrying out these workshops shall be described based on the third constituent of the framework.

7.3.4 Application of constituent 3 – Determining the product architecture

The aim of applying the third constituent within the context of this case study is to provide a basis for carrying out ideation workshops for considering AM in conceptualization. It shall be shown that principles can be used for providing knowledge about AM for the analysis and synthesis of product concepts. Therefore, the workshop structure shall ensure that design goals are clarified before, to generate suitable representations of the product.

Thus, in the following, a workshop concept will be lined out that has been applied twice within the described research project. The workshops served as a pilot program for establishing workshops for integrating AM into design processes company-wide. Therefore, the workshops were carried out in groups of 5 to 8 designers from different departments of the company within a duration of about three hours. As an initial situation, components of an automobile were given that were analyzed on the basis of predecessor products. The procedure of the workshops is leaned from the Basic PAD Method, resulting in the four steps as shown in Fig. 7.12. The steps comprise the following activities:

1. **Clarifying design goals**: The goals are clarified for the given components to be considered within the workshop, i.e., those issues that are most promising to be improved. For this, a goal chart is used, here demonstrated with the *PAD Goal Chart*.[10]
2. **Generating product models**: Representing the product in product models allows to create a shared understanding of the product and a basis for discussion. In the case of the workshops, due to limitation of time, only one model is generated that gives an overview of the functions as well as the spatial constraints of the components.

[10] Actually, in the workshops a specified goal chart was used, see Sec. 7.3.2.

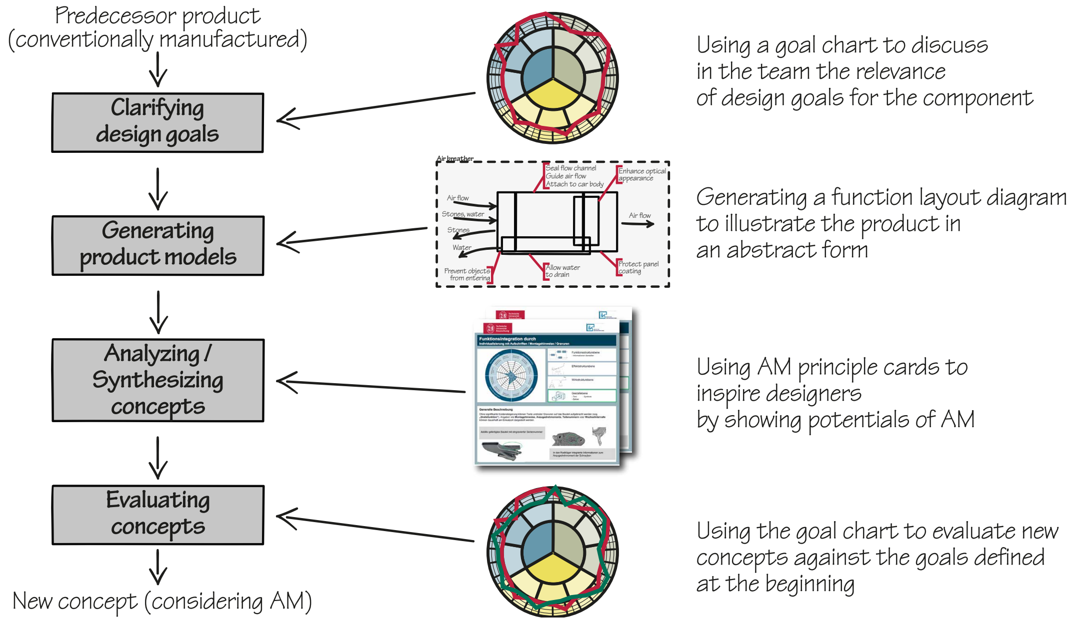


Figure 7.12: Procedure of carrying out the ideation workshop leaded from the Basic PAD Method

3. **Analyzing/synthesizing concepts**: The generation of new concepts is stimulated by principles cards comprising AM knowledge. The principles shall inspire designers to develop new ideas to be sketched on paper.[11]
4. **Evaluating concepts**: The resulting concepts are discussed within the group of designers to highlight their main advantages and disadvantages. For this, the goal chart applied in the first step is used to compare the new concepts to the desired state.

In order to give a short impression of the results of a workshop, as an example, the redesign of a component called *air breather* shall be described in the following. An air breather is mounted in the car body behind the front wheels of automobiles, see Fig. 7.13. It allows to discharge the air accumulated in the wheelhouse to the side of the car in order to compensate high pressure in the wheelhouse. Besides this practical functions, it has symbol value and serves as an important design feature. Conventionally, air breathers are made of injection-molded plastic, in some cases, supplemented by a cover made from fiber-reinforced plastics or chrome. Thus, various parts are assembled forming – broadly speaking – an air tunnel including guiding plates and filter grilles to prevent the entering of objects like pebble stones. Since the aerodynamic requirements and the available building space requires a complicated geometry, manufacturing restrictions only allow to produce this component out of several parts what increases costs.

[11]The principle cards used in the workshops are further described in [RWS+18] and [RSW+17].

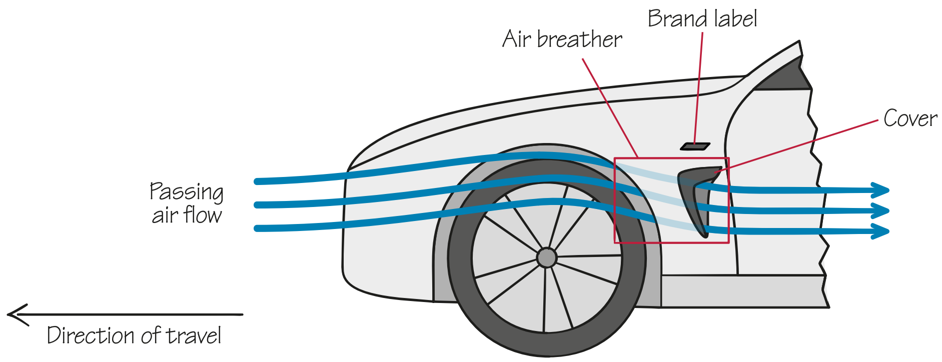


Figure 7.13: Illustration of an air breather behind the front wheel of an automobile

Within the workshop, first, the goals as illustrated in the goal chart in Fig. 7.10 have been identified. To address these goals, within the second step, the designers shall break cognitive barriers caused by the existing product solution by abstraction. Therefore, a product model is generated that shall explicitly *not* include the level of detail of a CAD model (that most designers have in mind). For this, a PA representation inspired by the *Product Architecture Notion* of Wie (R2) shall be used that allows to represent functions, as well as spatial constraints of the products, within one model that can be specified regarding various aspects like manufacturing, embodiment, or variety. Such a representation is especially suitable for workshops since it can be easily generated on a flip chart and can cover aspects of various levels of product models. An example of this diagram is shown in Fig. 7.14 that illustrates the main functions of the air breather, as well as the functions of neighboring systems that can potentially be integrated into the air breather. It the figure, only a part of the whole diagram is shown that only illustrates the air breather and a neighboring radar sensor. Beside these, other neighboring systems like the brand label, the flasher, the wash water tank, the wheel arch liner, etc.

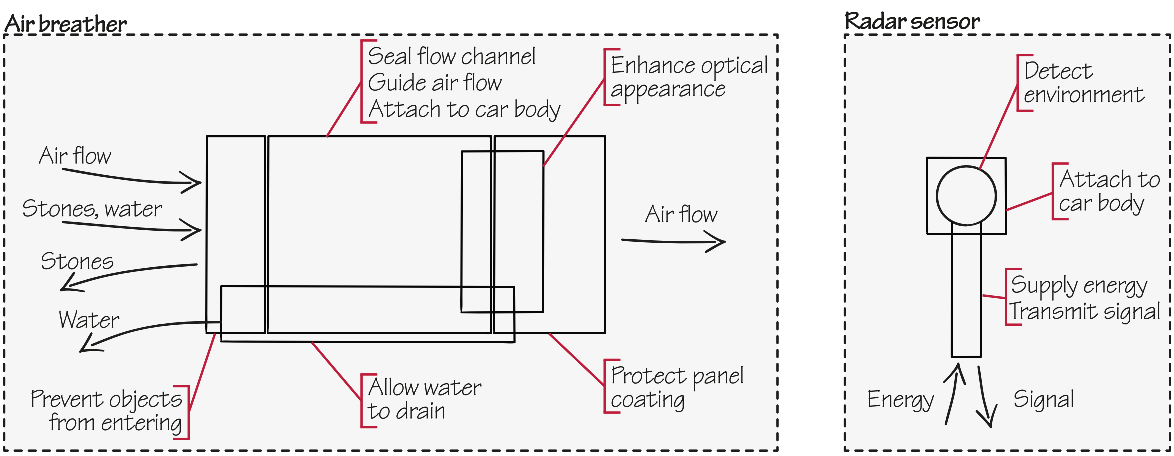


Figure 7.14: Representation of the functions of the air breather and a radar sensor (as an example for a neighboring systems)

By inspiring the designers with principles, various ideas were generated to be applied to the air breather. Tab. 7.5 shows examples of PAD principles applied to the air breather. Supported by these principles, designers generated new concepts that allowed to achieve various of the goals stated in Sec. 7.3.2. For instance, the principle *avoiding unnecessary partitions* enabled to integrate neighboring parts into the air breather. Thus, concepts were elaborated that integrated the brand label, the housing of the flasher, as well as the fixation of the radar sensor into the air breather. For the air breather itself, the number of parts could be reduced to one part due to the possibility to manufacture complicated geometries like guiding plates and meshes including cavities. In this way, potentials were tapped to reduce production costs, integrate new functionalities, to reduce size and weight.

Table 7.5: Examples of PAD principles proposed to be applied on the air breather

PAD principle	Application on air breather
P13: Integrate new functions by **extending capabilities**	AM provides the possibility to easily combine different materials, which allows to extend the capabilities of parts. For the air breather, it is considered to manufacture the visible parts from higher-quality materials.
P12: Integrate new functions by **exploitation of existing capabilities**	AM allows to fabricate individual surfaces of high fineness – a capability that is often not exploited. Thus, the air breather allows to include lettering of the model name of the automobile.
P14: Integrate new functions by **temporal switching modes**	AM allows to fabricate elastic structures. This allows to print covers on the air breather that deform at higher mechanical load occurring at higher driving speed. In this way, breathing grills can be realized that let pass higher amounts of air only at higher speed.
P2: Integrate design units by **avoiding unnecessary partitions** by using alternative manufacturing	Conventionally manufactured, plates for guiding the air flow and meshes for omitting the entry of objects need to be fabricated as separated parts. AM allows to include cavities in the parts. Thus, complicated geometries like plates and meshes can be integrated into the main part of the air breather.
P5: Integrate design units for **avoiding expensive assembly**	Parking sensors are conventionally integrated into the fenders, requiring specific installation points. AM allows to integrate electronic parts like sensors during the manufacturing process avoiding the assembly and design efforts.

Overall, the workshop concept provided insights into the application of the *Basic PAD Method* in limited time. The steps cover the main activities that were regarded as appropriate for the workshops in order to develop a shared understanding of design goals and the product under consideration. Especially, the application of principles provided inspiration for the designers to start with developing new product concepts.

7.3.5 Conclusion

The framework for product architecture design, obviously, has a more generic focus than supporting the introduction of AM into companies. This case studies aimed at demonstrating the transferability of the framework to more specific challenges in designing. The implementation of AM into design process of an automotive manufacturer provided an appropriate example for this since all three constituents could be applied. The first constituent was applied to allow designers to identify design goals that can be addressed by the implementation of AM. The second constituent allowed to analyze the established design process in order to understand at which stages product models are considered to integrate the consideration of AM at the most suitable stages. The *Basic PAD Method* of the third constituent represented a basis for carrying out ideation workshops that aimed at providing AM principles according to a similar pattern as included in the framework for product architecture design. The results of the workshops showed that suitable new product concepts could be elaborated.

The appropriateness for the validation of the framework is, obviously, limited due to the shifted focus of application. Nevertheless, the application provides evidence for the transferability of the framework. It has been shown that the key idea of the first constituent – to systematize goals regarding strategic goals of the company – enables designers to get a proper overview of potentials of AM. By applying the second constituent, it has not been outlined how PAD goals are addressed on the levels of product models. However, it could be shown that the general way of representing design processes allows to allocate design activities to stages most appropriate depending on which product models are required to apply specific design principles. By carrying out the workshops, it has been demonstrated that the *Basic PAD Method* is suitable to address the main activities for conceptualization. Thereby, the correlations between goals and product models as well as between goals and principles have been shown by referring to PAD principles included in the framework. Thus, in conclusion, the case study demonstrated how the generic framework can be adapted for specific design challenges where elements of the framework proved useful to be applied.

7.4 Discussion of the validation results

After providing insights into case studies, this section discusses the achieved overall results of these validation attempts. Therefore, the two types of validity introduced in Sec. 7.1 are considered separately: Sec. 7.4.1 will assess the logical validity regarding the five hypotheses. Sec. 7.4.2 will consider the validity of the acceptance in industry and academia.

7.4.1 Logical validity of the framework

According to the validation approach of this thesis, the logical validity of the framework can be proven in four steps. The case studies provide indications for the third step, the proof of the *empirical performance validity*. Therefore, it must be shown that the framework is useful within the chosen example problems, see Tab. 7.1. Thus, in the following, a conclusion shall be drawn on each of the five hypotheses whereas the results of the case studies only allow a qualitative evaluation.

Hypothesis 1: *The definition of representations of the product architecture (PA representations) against the background of an overarching consideration of basic PA levels increases the appropriateness of product models used within the design process.*

In both case studies, different PA representations have been applied in order to exploit the full scope of potentials of product architecture design. In the first case study, the conceptualization of a product platform demonstrated that PAD principles were applied on the basis of different PA representations (in detail shown for function structure, working structure, and module structure). Similar, in the second case study it was shown that AM entails alternative solutions that can be tapped on all five levels. In both cases, the database of PA representations allowed to access suitable PA representations from literature after filtering these regarding the levels and the PAD goals to be addressed. In this way, the PA levels provided a useful support in ordering PA representations according to the degree of abstraction considered in a specific stage of the design process.

Hypothesis 2: *The understanding of basic design stages within a design project including the consideration of available product models increases the designers' ability to allocate product architecture design to the most suitable stages of the design process (PAD stages).*

The underlying assumption for this hypothesis is that product architecture is often not considered at the most suitable point in time of a design process, for instance, too late. In both case studies, the application of the second constituent provided a basis for assessing design processes regarding the stages when the product architecture can be considered. The mapping of PAD goals with basic PA levels has lead to an identification of the most suitable stages for considering product architecture design (PAD stages). In this way, evidence could be provided to the hypotheses by assuming that it supports an improved understanding of the role of product architecture within design processes.

Hypothesis 3: *The representation and assessment of relations between strategic goals and design goals for product architecture design (PAD goals) increase the overall awareness of implications of product architecture design.*

Due to the variety of design goals that are affected by product architecture, designers are often fixated on single goals while neglecting others. Especially, the first case study has shown that the application of the PAD Goal Model allows overviewing the range of possible PAD goals within the categories of strategic goals. In this way, it could be ensured that possibly conflicting PAD goals are recognized by designers and can be prioritized according to the pursued business case defined by the main strategic goals. In the second case study, it has been shown that in the same way, AM goals can be allocated to the strategic goals proposed in the *PAD Goal Chart*. It has been demonstrated that the explicit classification of goals allows designers to recognize issues that are often neglected.

Hypothesis 4: *The provision of existing product knowledge as principles for product architecture design within a collection of basic principles (PAD principles) increases the accessibility and combinability of existing knowledge about the product architecture.*

Whereas most existing PAD approaches only include a reduced scope of PAD principles (often with a focus on specific goals), the case studies have shown that it can be suitable to combine different types of PAD principles. Thereby, the standardized way of provision within the database founded on the four basic PAD principles leads to an improved accessibility. In this way, in the first case study, PAD principles based on integration, differentiation, standardization, and variation were applied to develop a product concept most appropriate regarding all defined PAD goals. In the second case study, especially principles for integration inspired designers to consider alternative concepts compared to predecessor products. In this way, it have been shown that designers are enabled to generate new ideas during design on the basis of PA principles that are otherwise often not accessible for designers since it is scattered across different literature sources.

Hypothesis 5: *The normalization and provision of methods based on a basic method of product architecture design (PAD methods) increase the accessibility and combinability of methods for product architecture design.*

PAD approaches in literature mostly comprise methods that can hardly be compared and combined. The case studies have shown that the *Basic PAD Method* can provide a basis for carrying out various PAD activities whereas the generic procedure can be specified according to the specific design situation by specific PAD methods, PA representations, and PAD principles. Within the first case study, this approach has been proven as suitable to determine the PA in various stages of the design process. In the second case study, it was shown how the *Basic PAD Method* can also be applied for carrying out ideation workshops with a slightly shifted focus on AM instead of PAD.

In conclusion, regarding all five hypotheses, both case studies have revealed design tasks on which the framework could be applied. Therefore, the consideration of PA representations, PAD stages, and PAD goals as well as the support provided by PAD principles and PAD methods had proven useful in order to determine product architectures. However, this initial validation is limited to the application of the framework to two case studies. In some cases, especially, regarding the second constituent, the application has been carried out retrospectively. In this way, the actual benefits of the application could only be estimated. Furthermore, the application examples only allow to apply a limited number of knowledge elements included in the knowledge base. Nonetheless, it is assumed that the framework's usefulness can also be proven in further case studies, since the framework has been built on a solid foundation of established PAD approaches.

7.4.2 Acceptance of the framework

Besides the logical validity of the framework, the acceptance of the framework is a central element for confirming the utility of a new design support, see Sec. 7.1.2. This type of validity can only be achieved by transferring and applying the support to new environments. In the case of this thesis, this type of validity can only be proven to a very limited extent since the case studies did not provide the possibility, first, to integrate large groups of other persons into the application of the framework, and second, to carry out extensive interviews or surveys with the applicants. Thus, the validation is based on subjective impressions of the author within the two case studies and on feedback from colleagues in design research within the institute and from national and international conferences.

Thus, discussions on the framework have shown that, in general, a high necessity for overarching PAD approaches is given. Designers, as well as researchers, struggle in overviewing the variety of existing approaches, which is the reason why various researchers are currently aiming at integrating different approaches, e.g. [BHB+16, KG18, OHS+16]. Also in design practice, the case studies and further design projects have shown that product architecture is recognized as a central issue of designing. However, the design approaches actually applied in the companies do not exploit the potentials of what the state of the art provides. Therefore, the relevance of the presented work has turned out as generally high.

The acceptance of the result of presented work, the framework for product architecture design, has been presented with different focuses on various conferences (see list of publications in appendix). A high usability was assumed, especially, for the comprehensive goals model (constituent 1), as well as the structured provision of PAD principles and PAD methods (constituent 3). The approach, to classify PA representations on levels was considered as useful (constituent 2). However, it was seen that in the community no shared understanding of the definition of those levels exists. Furthermore, in academia as well as in design practice, a high necessity for quantitative approaches for designing the product architecture was seen. Even though the framework provides links, for instance, between PAD goals, appropriate PA representations to address these goals, PAD principles and PAD methods for implementation, the framework does not support the quantitative evaluation of the solutions.

Moreover, in some cases, the framework is seen as complicated in its application as it proposes different elements (the three constituents and the software tool) that have to be understood and applied. Other approaches in literature include only one procedure with supporting tools for each step that appear more easy to apply. However, partly, the complicated nature of the framework is caused by the fact that its value is rather rooted in breadth than in depth. A wider breadth requires the integration of various elements whereas other more specific approaches get along with less elements.

In summary, the validation of the acceptance of the framework is only based on subjective impressions of the author in various design projects and conferences. However, it is supposed that the relevance of the research topic and the general approach of the framework are generally accepted in design practice and research. However, the applicability seems to suffer from the comprehensive organization of the framework. For this reason, it is seen as highly important to gather feedback of more persons regarding the applicability of the constituents and the tool in order to improve the acceptance at further steps of development of the framework.

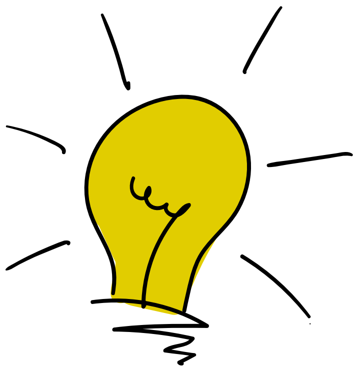
7.5 Conclusion

The objective of this chapter was to provide an initial validation of the framework for product architecture design. Initially, it was stated that the validity must be proved by confirming the logic of the framework and its acceptance in design practice and academia. For this purpose, two case studies have been described in which the application of the three constituents of the framework and the software tool were demonstrated.

Thereafter, the overall validity of the framework had been discussed regarding the logical validity as well as the acceptance.

Besides the illustration of the application of the framework, the key insights of this chapter are the statements on the framework's validity. Therefore, the logical validity of all hypotheses could be proven. Further needs are given to show its transferability to different contexts. However, especially, for the second hypothesis on the integrity of PAD into design processes, the case studies did not provide sufficient examples for validation. The acceptance of the framework, i.e., the utility as seen by researchers and practitioners, could only be discussed to a very limited extent since no interviews have been conducted. Nevertheless, first feedback from the design projects and conferences has revealed a general acceptance of the research approach and the framework. However, special focus of further work shall be put on the ease in applying the framework that is partly regarded as complicated due to the great number of elements.

Thus, in this chapter the *Descriptive Study II* is completed and allows a conclusion of the development of the framework for product architecture design. Based on this, Chap. 8 will summarize the results of the thesis and provide an outlook to further steps arising from the presented work.



8

Conclusion and outlook

The presented work constitutes an approach towards an overarching understanding of product architecture design. Thereby, the line of argument is oriented to the target group of designers dealing with the phenomenon of product architecture design. Their situation is observed, their needs are formulated, and a framework is developed to support them during designing. This chapter will conclude the assumptions on the improvements achieved for designers as well as researchers in the field of product architecture design.

The structure of this chapter is constituted by four sections: In Sec. 8.1, the content of this thesis will be summarized. In Sec. 8.2, the main contributions will be highlighted with regard to the use for designers and researchers. In order to show the limitations of these contributions, Sec. 8.3 will deal with a reflection of the approach of this thesis. Finally, in Sec. 8.4 an outlook on directions for further research will be given.

8.1 Summary

The motivation of the presented work was set up by observations in design practice described by three assumptions: First, designers do not recognize all implication of product architecture. Second, designers struggle in identifying the most appropriate methodical approaches to determine the most suitable product architecture. Third, designers are not able to integrate product architecture design at the most appropriate points in time within design processes. Based on these assumptions, in Chap. 2, a review of literature was conducted highlighting the variety of existing approaches supporting product architecture design. However, it was also shown that the existing knowledge is not well connected and not consistent among each other.

This provided a sound starting point for the research conducted in this thesis that has been structured along three research questions: RQ-1 aims at identifying influence factors on the success of PAD in design practice (*Descriptive Study I*). Based on these factors, RQ-2 deals with the elaboration of a new design support for PAD (*Prescriptive Study I*). Finally, RQ-3 considers the validity of the new design support (*Descriptive Study II*). The achieved answers to these three questions are summarized in the following.

Descriptive Study I: Influence factors on product architecture design

RQ-1: *What factors within a product design process influence whether and by which supporting means the product architecture is considered in design practice?*

The factors influencing the success of PAD are various. In Chap. 3 a comprehensive analysis of literature has been conducted identifying twelve influence factors of a significant importance. Regarding these twelve factors, interviews with designers have been carried out that confirmed the relevance in design practice. In order to set the focus of this thesis, the influence factors have been clustered into five groups that correspond to the five fields of design research introduced in Chap. 2. According to these five fields, five sub-research questions have been formulated of that each had one influence factor in focus: the suitability of product models used in product architecture design (RQ-2.1), the point in time to consider product architecture (RQ-2.2), the recognition of implications of product architecture (RQ-2.3), the availability of decision-support (RQ-2.4), and designers' knowledge for applying methodical approaches (RQ-2.5). In this way, a basis was provided for the purposive development of a new design support.

Prescriptive Study I: Elaborated framework for product architecture design

RQ-2: *How can designers be supported determining the most suitable product architectures?*

For answering this question, in Chap. 4, the key concept of the new design support was outlined by five hypotheses. The hypotheses provided initial answers to the five sub-research questions by postulating approaches on the systematization of the PAD knowledge already existing in PAD approaches. Accordingly, five types of knowledge elements could be distinguished: PA representations (Sec. Hypothesis 1), PAD stages (Sec. Hypothesis 2), PAD goals (Sec. Hypothesis 3), PAD principles (Sec. Hypothesis 4), and PAD methods (Sec. Hypothesis 5). Based on this basic understanding of PAD approaches, in Chap. 5, various PAD approaches were analyzed in order to demonstrate how knowledge elements can be extracted from the existing approaches in order to be classified within an overarching framework. To transfer this knowledge into design practice, in Chap. 6, three constituents of the framework were developed: for supporting the recognition of PAD goals, for integrating PAD into design processes, and for determining the PA. Additionally, a tool was developed that provides the required knowledge elements within a database. In this way, a framework applicable in design practice was created allowing designers to identify and apply PAD knowledge by combining it within design supports customized to their specific needs.

Descriptive Study II: Validation of the framework in design practice

RQ-3: *How does the elaborated support improve the determination of the product architecture?*

The application of the framework was demonstrated in two case studies in Chap. 7. The first one dealt with the development of a product family of air preparation units. The second one dealt with the exploitation of potentials of additive manufacturing by an explicit consideration of product architecture. The case studies provided insights into the logical validity of the hypotheses providing evidence to the utility of the three constituents. Obviously, the case studies covered a limited scope of possible application contexts of the framework. Therefore, they only constitute a first step towards an extensive validation of the framework. Besides the logical validity, first assumptions on the acceptance of the framework were made. It was concluded that the application of the framework possibly appears, on the first glance, complex to designers and researchers due to the breadth of the support's content. Thus, the focus of further work shall be laid on the facilitation of its accessibility for which the developed tool provides a suitable basis.

8.2 Main contributions and novelty

The central contribution of this thesis is the support for product architecture design. The basis for this was provided by an extensive analysis of the phenomenon of product architecture design to understand the designers' needs as well as the constituents of existing methodical approaches. As a result, a framework was presented providing an overarching structure for methodical knowledge that is proposed by established PAD approaches. Thereby, the following three contributions shall be highlighted as most useful:

- **An overarching understanding of product architecture design**
  In literature, product architecture is defined in various ways since different issues can be addressed by its consideration. However, this impedes the comparison and combination of existing valuable insights. Within this thesis, an overarching understanding of the term as well as the phenomenon of product architecture design have been

provided. Therefore, the dimensions of *structure*, *allocation*, and *commonality* have been differentiated for generating appropriate representations of the product architecture. Based on this, approaches can be captured in a more differentiated way to relate different types of knowledge elements as PA representations, PAD stages, PAD goals, PAD principles, and PAD methods in relation to each other. Comparable theories on product architecture design do not yet exist, since other works only consider specific perspectives on product architecture design.

- **Systematization of existing methodical knowledge**
  Based on the five types of knowledge elements, an analysis of existing approaches was carried out. Depending on the demands within specific design situations, designers and researchers can access these knowledge elements. In this way, for instance, designers can obtain an overview of PAD goals and prioritize these according to the relevance to their design tasks. Appropriate for these PAD goals, they can make a selection of PA representations proposed in literature and apply these in order to elaborate new product concepts supported by an extensive collection of PAD principles and PAD methods. In this way, designers are able to access those knowledge elements that are relevant to them within *one* framework – without having studied all approaches existing in literature. The knowledge elements currently included in the software tool provide a sound overview of existing knowledge in established approaches.
- **The constituents of the framework supporting product architecture design**
  For allowing designers to access the knowledge elements appropriately, the framework's constituents provide a situational support that guides designers through the recognition of PAD goals, the integration of PAD into design processes, and the determination of the product architecture. The constituents are provided in a generic form to be specified according to the specific design situations to finally achieve a customized PAD approach. Especially, the support of the software tool proved useful for allowing designers to handle the variety of existing and possibly relevant knowledge, and to select and apply the knowledge elements most appropriate.

Besides these contributions to product architecture design, another valuable insight has been gained by the extended and specified model of design research. From the author's perspective, this model allows to describe various phenomena within designing and can contribute towards a wider understanding of methodical approaches. By the transfer of the model to product architecture design as carried out in this thesis, it has been shown that it is valuable to differentiate and systematize design goals, product models, process models, principles, and methods. It was highlighted that the provision of these elements shall be carried out by representing the relations in between, for instance, between a principle and a corresponding addressed goal or a product model underlying the application. However, besides this application in the field of product architecture design, it appears expedient to transfer the comprehensive perspective on designing on other fields of design research to structure design knowledge. The here presented approach provides a thoroughly elaborated and validated example for further works.

8.3 Reflection of the results achieved

The research carried out within this thesis, naturally, includes limitations regarding the added value to design practice and academia. Therefore, in this section, the research approach will be reflected first, before the validity and the transfer and implementation of the results will be discussed.

Origin and objective of the research

The problem stated at the beginning of this thesis had been arisen by personal experience of the author with the application of methodical approaches, especially, for modularization, platform design, and function integration. During the application of those approaches in industry projects, the issue became apparent that single approaches from literature only cover a restricted scope. For instance, many approaches focus on product variety whereas they ignore other implications of product architecture like on the product weight or the company's flexibility to react to product changes.

For this reason, this thesis delivered an overarching framework including the knowledge of different approaches. However, in the end, the question must be raised whether the focus on product architecture is appropriate to address issues in design practice. After all, do designers ask for a support for product architecture design, or do they rather require a specific approach for addressing design goals like reducing variety, increasing changeability, or reducing weight? If the latter is the case, the framework for *product architecture design* appears to be a detour to the actually required support since it provides a generic approach. Therefore, the initial definition of the objective of this thesis may appear to designers and researchers as rather academic than oriented on real issues from practice. However, for the reason of the academic definition of the scope of this thesis, a result has been delivered that goes beyond usual boundaries of consideration within design research. In the end, the necessity for this integration of approaches has proven useful within the presented case studies since it has been shown that single issues of product architecture design are often related to others. The generic approach of the framework reduces the possibility to overlook these related issues.

Validity of the results

In order to prove the validity of the results achieved, case studies have been carried out. Thereby, the validity has been considered from the perspective of the logical validity and the acceptance. Regarding the logical validity, the case studies dealt with two specific design tasks. These tasks only covered a small amount of the scope of the framework's field of application, for instance, by resulting in the application of only a few principles of the comprehensive collection. Nonetheless, the logical validity could be demonstrated in terms of expedient guidance of the designers by the constituents, especially, by the knowledge base included in the software tool. Even though, in that way, only single paths through the framework have been shown, it proved the usefulness of the access to knowledge. Further case studies will allow to achieve a comprehensive validation.

The acceptance of the framework could only be proved by a small number of persons that have applied the framework by guidance of the author of this thesis. Therefore, the value of this validation can only provide a starting point for further cases of application within contexts including persons without personal relations to the author. In those case studies, especially, the acceptance of the software tool has to be examined since its validation was not part of this thesis.

Transfer and implementation

The transfer and implementation of the framework is important since various methodical supports are developed in design research, but do not find their way into application, in some cases. Reasons for that can be that the approaches are not as specific as required in industry or published only in a way covering aspects relevant to research [BGB+16:1185]. Undoubtedly, these issues also apply to this thesis since it arguments its thread against the background of generic theories on design research and describes the results in a way focusing on the comprehensibility from an academic perspective. Moreover, the transfer of the framework to design practice was shown in case studies that were accompanied by the author. It was not tested how the framework can be transferred and implemented within new environments without the participation of the author. However, this was not included in the scope of this thesis, which ended with an initial validation. After carrying out further case studies for validation, therefore, the focus in a possible *Prescriptive Study II* has to be on the elaboration of flanking approaches for transferring the framework to research education of students and design practice. Existing environments in the Institut für Konstruktionstechnik, for instance, the method portal *Methodos* and the corresponding training concepts can provide a basis for this, cf. [Bav18:131ff.,173ff.].

8.4 Directions for further research

In addition to the before described further activities regarding the validation of the framework and its transfer to design practice, the limitations of the presented work offer a number of opportunities for future research. Thus, the following challenges towards an extension of the framework and a transfer to related research topics can be tackled:

- **Extension of the framework's constituents**
  The constituents of the framework provide an expedient basis for carrying out activities dealing with the phenomenon of product architecture design. Extensions of these constituents are conceivable to improve their handling and scope. Thus, for the first constituent, further guidelines can be elaborated that support designers deciding on the relevance of single design goals. Currently, the *PAD Goal Chart* provides an structured overview of 27 PAD goals to be prioritized. However, to facilitate the handling of the large number of goals, a pre-filtering of the goals can be implemented that reduces the number of goals on the basis of general criteria to describe the design task, for instance, whether variety is important or not. In that way, the scope can be reduced and goals can be presented in a more specific way. The second constituent only includes a very limited perspective of modeling of design processes including product models and process stages. By including further perspectives on design processes, additional support can be provided for integrating PAD. Examples for those further aspects are the stakeholders involved in the development, cf. [VS13:18ff.], or methods and tools applied within the stages, cf. [BHI+18:149ff.]. The third constituent, which strongly depends on the application of the software tool to access knowledge elements, can benefit from a customized representation of the knowledge. While the tool is currently used to filter and browse the results, a customization of the knowledge base is not possible. Therefore, it would be beneficial for designers to select, save, and edit results according to specific contexts.
- **Extension of the knowledge base of the framework**
  The knowledge elements (PA representations, PAD principles, etc.) included in the framework respectively the tool represent an initial selection. This selection can be extended by adding further elements from literature. Therefore, further approaches focusing on specific design goals, for instance, reducing weight or increasing flexibility can be analyzed in order to classify further knowledge elements. Besides this, also

experience from design practice can result in the formalization of new knowledge. These insights can provide useful examples for the validation of links within the framework, for instance, on the links between PAD goals and PAD principles.

- **Adaption for addressing specific design issues**
  As shown in detail in the second case study, the framework can be applied in specific contexts, like Design for Additive Manufacturing (DfAM). In future works it is planned to develop specific goal models, principles, and methods with a specific focus on DfAM. For this, the presented approaches will be extended, finally, aiming at the development of a software tool specific for DfAM, cf. [RWS+18]. Likewise, the concept of the framework can be used for the development of further specific supports. Thus, it is planned to transfer the framework to the provision of Industry 4.0 solutions to be integrated into design processes. Similarly to product architecture design, in this field, various knowledge is being developed that can be systematized regarding the design goals to be addressed, the product related design principles and the methods to implement it. For this, the architecture of the software tool can provide a basis.

In conclusion, the presented framework provides possibilities to be further developed regarding product architecture design and design research in general. Thus, its usability for product architecture can be improved by extending the methodical support of the constituents and the scope of the knowledge base. Moreover, this thesis has presented a generic approach for supporting design that can be applied to other fields of design research. For both, the most valuable insight of this thesis is the clear differentiation and combination of types of knowledge. This concept can provide a basis for the development of well-structured methodical supports for various fields.

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Glossary of terms

Additive manufacturing is a class of manufacturing processes in which material is joined or solidified under computer control to create three-dimensional products with material being added together. 188

AM see: additive manufacturing 188

Analysis allows designers to understand the product properties, for instance, by discovering the product's weight by modeling the products geometry. 24

Approaches for product architecture design comprise a specific class of methodical supports used in designing (including methods, procedures, tools, etc.) that support the design of the product architecture. 15

Building (B) structure describes the embodiment of technical elements as components and their interactions as interfaces. It describes the product's geometry as it is manufactured.

Design goals anticipate a future state of the product that is preferred to the current one by describing its required product properties. In this way, design goals guide designers through activities of analysis and synthesis of solutions for the design task. 32

Designing comprises all activities aiming at the determination of characteristics of a product in order to fulfill the required properties of the product. 13

Design methods are expedient representations of process-related knowledge containing statements on how specific arrangements of process characteristics (e.g., through providing recommended sequences of activities) implicate process properties (e.g., through providing rationales on how design goals can be achieved). In this way, design methods can guide designers through the process of solving specific problems based on approved process knowledge. 40

Design phenomenon is an observable or imagined episode or articulation of designing that is studied by researchers in design practice in order to improve it by the implementation of a methodical support. 70, 90

Design principles are expedient representations of product-related knowledge containing statements on how specific arrangements of product characteristics implicate product properties. In this way, design principles can enhance designers to apply already gained knowledge to new design problems. 35

Dimensions of PA representation describe classes of product characteristics that are included in PA representations: structure within a product model, allocations between different product models, and commonality within a product assortment. 41

Effect (E) structure describes physical, chemical, biological etc. effects and their interactions. It describes how to fulfill the required sub-functions.

Function (F) structure consists of sub-functions and their interactions. It describes the teleology of the product, i.e., what it is for.

Goals for product architecture design (PAD goals) include those design goals described as preferred future states of product properties that are implicated by the product architecture within different phases of the product life cycle. 51, 53, 84, 85, 87, 100

Knowledge involves all abilities, skills, and expertise of designers for solving problem. 33

Methods for product architecture design (PAD methods) are expedient representations of process-related knowledge containing statements on how specific activities concerning product architecture design implicate process properties (e.g., through providing rationales on the achievement of PAD goals). 62, 64, 85, 87, 106

Models (used in design) are purpose-dependent abstract reproductions of real objects (e.g., the product to be designed, or the design process). Models allow designers to analyze and synthesize the modeled object. 14

Module (M) structure describes physical and/or organizational aggregation of components as modules and their interactions. It describes the product passing through different product life phases (development, distribution, repair, etc.).

PA see: product architecture

PAD see: product architecture design

PAD approach see: approach for product architecture design 15

PAD goal see: goal for product architecture design

PAD principle see: principle for product architecture design

PAD stage see: stage for considering product architecture design 49

PA method see: method for product architecture design

PA representation see: representation of the product architecture

Phenomenon model includes those observations of the reality of design practice that are relevant for the employment and reflection of design tools. 90

Principles for product architecture design (PAD principles) are expedient representations of product-related knowledge containing statements on how specific designs of the product architecture implicate product properties, and therefore, contribute towards the achievement of design goals. 56, 58, 85, 87, 103

Process models are representations of the design process (under definition) comprising all information required within specific design situations to evaluate relations between process characteristics and process properties. In this way, they allow designers to analyze the process properties and synthesize the process characteristics. 28

Product architecture describes the structures of elements within product models (e.g., function structures or component structures) and/or the allocations of elements of different product models (e.g., allocations between functions and component). The consideration of the product architecture can include only single products or include the commonality regarding several products within a product assortment. 2, 44

Product architecture design (PAD) comprises all activities aiming at the determination of the architecture of a product, e.g., of how elements of a product are arranged. In this way, product architecture design contributes to the fulfillment of a wide range of product properties that are affected by product architecture. 15

Product characteristics describe the appearance of a product, for instance, its structure, shape, dimensions, materials, and surfaces. They can be directly influenced or determined by the designer. 24

Product models are representations of the product (to be designed) comprising all information required within specific design situations to evaluate relations between product characteristics and product properties. In this way they allow designers to analyze the product properties to synthesize the product characteristics. 25, 95

Product properties describe the product's behavior, for instance, weight, safety, reliability, aesthetic properties, manufacturability, testability, environmental friendliness, and cost. They can not be directly influenced by the designer. 25

Representations of the product architecture (PA representations) describe the structures of elements within product models (e.g., function structures or component structures) and/or the allocations of elements of different product models (e.g., allocations between functions and component). The consideration of the product architecture can include only single products or include the commonality regarding several products within a product assortment. 41, 44, 84, 87, 95

Stages for considering product architecture design (PAD stages) describe the process integrity of product architecture, i.e., in which stages of the design process activities related to the determination of the product architecture are allocated. 49, 84, 87, 97

Synthesis allows designers to determine product characteristics, for instance, by finding new concepts for the embodiment in order to reduce weight. 24

Working (W) structure consists of working bodies and their interactions on working surfaces. It describes how to realize the required effects.

Appendices

A Definitions of product architecture

Table A.1: Definitions of *product architecture* and related terms

Author	Literature	Definition
Ulrich	[Ulr95:420]	In informal terms, the architecture of the product is the scheme by which the function of the product is allocated to physical components. I define product architecture more precicely as: (1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specifications of the interfaces among interacting physical components.
Yassine and Wissmann	[YW07:118]	Product architecture defines the functional requirements within a product system, maps these requirements to physical elements or subsystems, and describes the interaction between these physical elements.
Eppinger and Browning	[EB12:18]	Product architecture is the arrangement of components interacting to perform specified functions. The architecture of a product is embodied in its components, their relationships to each other and to the product's environment, and the principles guiding its design and evolution. The terms product architecture and system architecture are used interchangeably in certain contexts.
Harlou	[Har06:83]	An architecture is a structural description of a product assortment, a product family or a product. The architecture is constituted by standard designs and/or design units. The architecture includes interfaces among units and interfaces with the surroundings.
Harlou	[Har06:85]	A product architecture is a class of architectures that covers one individual product. A product architecture is constituted by existing standard designs, existing design units, future standard designs and future design units. The architecture includes interfaces among the units and interfaces with the the surroundings.
Crawley et al.	[CWE+04:2]	System architecture is an abstract description of the entities of a system and the relationships between those entities.

Tab. A.1: Definitions of *product architecture* and related terms (continued)

Sanchez	[San07:103]	A product architecture is created by (a) decomposing a product design into a system of functional components, and (b) fully specifying how individual components will interact with other components in that system of components.
Wie	[Wie02:6]	Fundamentally, architecture is about a set of items and how they are arranged.
Wie	[Wie02:1]	Architecture design, also thought of more loosely as layout design within the context of conceptual design, is one stage of the mechanical design process that significantly impacts product performance in terms of manufacturing, assembly, modularity, product family variety, maintenance, etc. This step in design is special because it marks an occasion when many effects, including geometric concerns, come into play simultaneously on a large scale.
Fixson	[Fix05:346f.]	[Product architecture is] a comprehensive description of a bundle of product characteristics, including number and type of components, and number and type of interfaces between those components, and, as such, represents the fundamental structure of the product.
Andreasen et al.	[AHM96:17]	The structure of a product is the way in which its elements are related, seen from an expedient angle[12].
Xu et al.	[XGF08], cited from [SJS+14:4]	A concept for describing relations among components and connecting the functions to the components in a product. Platform architecture describes the logical relations between common and unique elements for enabling highly customized products based on customer preferences
Cutherell	[Cut96], cited from [SJS+14:4]	Modular architecture: functions-components mapping for minimizing inter-module interactions. Integral architecture: performance-driven or cost-based architectures, enabling variety, product change, and engineering standards.
Fixson	[Fix05:346f.]	[Product architecture is] a comprehensive description of a bundle of product characteristics.

[12] angles later specified as: function-oriented structuring and product life-oriented structuring

Tab. A.1: Definitions of *product architecture* and related terms (continued)

Erens and Verhulst	[EV97:6]	The composition of a product from a number of component products is a product architecture. It describes the components, together with their interfaces and operation. Each level in the product hierarchy has its architecture. Depending on the type of components, we speak about a functional, technology or physical architecture.
Erens	[Ere96:8]	A set of modules connected through interfaces and performing a certain operation. A product architecture partitions the solution space of design, sets conditions for a further decomposition of these modules and specifies the application of these modules in a bigger whole.
Kahn	[Kah12:462]	Product Architecture: The way in which the functional elements are assigned to the physical chunks of a product and the way in which those physical chunks interact to perform the overall function of the product.
INCOSE	[INC14:261]	[Architecture describes] fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution.
Krause and Gebhardt	[KG18:276]	Product architecture: Combines the product structure as physical arrangement and the function structure as functional description of a product, and sets their elements in relation to each other. Product architecture is the the functional and physical description of a product as a whole.[13]
Martin and Ishii	[MI02:214]	A family architecture implies that the different products have a common arrangement of elements, common mapping between function and structure, and common interactions among components. A product family architecture only exists if this commonality is present.

[13]translation by author

B Influence factors on product architecture design

In Sec. 3.3 twelve influence factors are introduced that are assumed to have a direct or indirect effect on the success of product architecture design. The factors are categorized according

- the addressed design goals (G),
- the applied design support (S),
- the available information about the product (I),
- the aspects related to the designers (D), and
- the company's organizational environment (E).

Whereas the twelve corresponding factors only been described briefly in Sec. 3.3, at this point, a more detailed description will be outlined referencing exemplary literature sources, mentioning the factors. In the following the factors are structured according to the categories described above:

B.1 Addressed design goals

Factor G1: Recognition of implications of the product architecture: As it was shown in Sec. 2.5 product architecture design affects various product properties like weight, adaptability, or manufacturing cost. The recognition of these implications sets the pre-condition for designers to consider the product architecture within decision-making. Otherwise, the product architecture will be determined *implicitly* during "the normal course of designing" resulting in a primary focus on properties like product performance, while product architecture implications are neglected or of secondary importance [CWE+04:1,20]. This may result in non-optimal architectures, or if considered in later phases, in an "cumbersome and inefficient path" of designing [Wie02:4]. Therefore, many approaches aim at an early anticipation of implications of the product architecture in order to allow designers to consider the product architecture explicitly by recognizing these implications when formulating and keeping track of design goals, cf. [Ren07, UE12, YW07].

Factor G2: Comprehensiveness of goal monitoring: At any point of the design process, designers need to be able to assess design decisions against all relevant design goals. For instance, when recognizing the relevance to reduce variety as one design goal, decisions have to be assessed regarding further possible goals, for instance, product performance, weight, or robustness [Wie02:4f.]. Thereby, goal conflicts can arise, for instance, when the modularity of a platform concept (addressing variety in the first place) lacks of robustness reduced by the large number of interfaces between modules [EV97:8]

[Ere96:235ff.]. Therefore, many approaches aim at a comprehensive understanding of implications of the product architecture by considering various life phases of the product in comparison [Ble11, Eri98, Ste10], or by opposing implications of different design principles, e.g., on integration *and* modularization [GK08, KK08, PBF+07]. Thus, for product architecture design, it is not sufficient to be able to set design goals in relation to the product architecture (G1), but to continuously check against beneficial or conflicting side effects on various other possible design goals.

B.2 Applied design support

Factor S1: Availability of decision-support: Success of designing is mainly based on the knowledge accessible to designers. This knowledge can be available as *tacit knowledge* "stored" subconsciously in the experience of the designers, or as *explicit knowledge* tangible and formalizable in the form of procedures or principles [Vaj14:392], see Sec. 2.2.4. In order to qualify designers for product architecture design, explicit knowledge is required including various approaches for product architecture design, for instance, as design principles or design methods. A central challenge is to make this existing knowledge accessible for designers appropriate for specific situations, cf. [Gaa10:34]. However, the existing literature lacks an appropriate systematization of this knowledge and designers are not able to access required decision-support appropriately, cf. [OHS+16:1] [BHB+16:489] [Zie12:62ff.].

Factor S2: Appropriateness of product models: Product models are used within designing to represent those information required for supporting specific decisions within a design process, see Sec. 2.2.1. Product models only comprise an extract of all information available on the product. Thus, also representations of the product architecture must be chosen according to those aspects of the product architecture most relevant, see Sec. 2.3. However, the product architecture can be considered within different product models like function structures, working structures, component structures, etc. [Cae91:43ff.] [Kip12:79ff.] and with a different focus on addressed goals [Deu15:53ff.]. Consequently, existing approaches for product architecture design propose various different product models for decision-making depending on the specific purpose of the approach. Therefore, it is required to enable designers to generate product models most appropriate for specific situations, and, if necessary, to interlink different product models representing aspects of the product architecture.

Factor S3: Integrity of product architecture considerations: Since facets of the product architecture are comprised within different types of product models, the product architecture can be considered within different stages of the design process [CWE+04:4].

Existing approaches for product architecture design define specific stages in which the approaches should be applied, for instance, in early phases, e.g. [SWC00] [Sed10], or in late phases when information about the embodiment design is available, e.g. [Eri98] [EB12]. Thus, decisions on the product architecture are often supported based on product models of different concretization corresponding to the current stage. However, in most cases, an overarching structure of these approaches is missing resulting in a lack of integrability of the different product models impeding a consistent consideration of the product architecture within the process [OHS+16:1]. Thus, it is required to describe approaches for product architecture design flexible regarding the integration into specific design processes with established product model landscapes, making the capability to adapt to specific design goals and available information possible [Deu15:18].

B.3 Available information about the product concept

Factor I1: Scope of system consideration: Products are often decomposed into subsystems, for instance, in order to allow a division of labor by reducing the complexity of the development task. In many cases, this decomposition is made according to the assembly structure of the product [VDI93:10], or according to different domains integrated in the development [Jan06:10ff.]. Within product architecture design these structures of the product are considered against the background of, for instance, integrating components of different subsystems [Zie12:174] or defining modules crossing borders of subsystems [KG18:129ff.]. However, this is only possible when the predefined structures and system boundaries can be consolidated by designers comprehensively, for instance, when components of different subsystems are integrated for reducing weight or building space [LSD+16, WIP16], or platforms are defined across product boundaries within the product program, e.g., for reducing variety [Har06, Ren07]. Therefore, it is crucial to define the scope of system consideration appropriately for a high exploitation of potentials of product architecture design.

Factor I2: Concretization of product concept: The assessment of design goals requires information from different business sectors of the company [YW07:121ff.], or, in other words, from different stakeholders involved in various phases of the product's life [KG18:105ff.]. However, not at any time in the design process, and not in each designers' position within the company, all available information match the concretization required for decision-making. Nevertheless, decisions on the product architecture often have to be made at a specific points in time of the design process, for instance, when subsystems for simultaneous development have to be defined early for allowing development work in parallel, e.g. [VDI93:10]. The challenge is to provide information of an appropriate information lavel for each decision on the product architecture. However, in many cases, it is inevitable to plan iterations and recursions within the design process [Zie12:63ff.] [Deu15:161].

B.4 Aspects related to the designers

Factor D1: Designers' method knowledge: The availability of method knowledge of the designers is a precondition for the application of methods for product architecture design. Only designers overviewing and understanding the existing methods can take benefit of what is presently available as support. However, for design research in general, such an overarching systematization of existing methods is missing in many cases [Ara01:195] [BC09:5] [Bav18:69ff.]. Particularly, OTTO et al. claim the application of methods for product architecture design as "inhibited by the seemingly broad array of material without a coherent organizing structure to compare development process tasks and the associated available methods and tools" [OHS+16:1]. Therefore, current research activities do not only focus on the development of new methods for product architecture design, but enhance the competencies of designers to use and combine the existing methods, for instance, for modularization [BHB+16] [BGB+16], platform development [Fir03] [MPN+08], and function integration [Zie12]. Thus, it remains a central challenge of design research to bring a structure into the existing knowledge on product architecture design in order to provide it in a proper form to designers.

Factor D2: Designers' mindset: Besides the designers' method knowledge, the designers' mindset is of high importance. The mindset comprises the understanding of a method's use "in accordance with the designer's reality (interpretation of task, situation, execution, validation, etc.), and the method's background and proper use" [AHC15:57]. After DAALHUIZEN the mindset entails at least three elements [Daa14:54f.]: The designer's beliefs about a method, the designers' trust in the ability to use a method beneficially, and the designers' preference for using a method. Supporting product architecture design, many methods are described in literature. However, several authors see a lack of a successful transfer of these methods into design practice caused by inappropriate descriptions of the methods and a lack of a proper designers' mindset, cf. [BGK14:123] [OHS+16:1] [GBK14:187f.]. Thus, for a successful implementation of design methods it is required to enable designers to understand the proper context and phenomena related to the methods' application and to make designers *wanting* to use the methods [AHC15:57]. An approach to enhance the designers' mindset is to enhance the provision and facilitate the utilization of methods by implementing visualization techniques, cf. [Har06:166] [Kip12:62f.] [Ble11:18]. In this way, the ease of learning and using is enhanced.

B.5 Company's organizational environment

Factor E1: Freedom of decision: For decisions to be made during the design process the freedom of the designers' choices can be limited due to many factors. Besides technical, like a solution space restricted due to prescribed requirements, in many cases organizational aspects play a central role to be focused on within this influence factor. Regarding product architecture design, the freedom can be limited, for instance, due to non-negotiable decisions made by co-working design teams concerning other subsystems [Zie12:174], different prioritization of goals by different stakeholders involved in the design process [VHS15:24ff.], or overarching strategic decisions regarding the product program of the company [KG18:134]. For that reason, it is a mayor challenge for product architecture design to get support and involvement from the entire organization [SMW+06:7] and to integrate all stakeholders concerning product architecture designs in order to find solutions most suitable for the overarching strategic design goals [LI14:103ff.] [OHS+16:13].

Factor E2: Point in time of product architecture consideration: The point in time within a design process is crucial for two parameters influencing decision-making [Vaj01:3]: First, the information available to make reliable decisions on the product, and second, the possibilities to influence the product concept. By progressing in the process the information about the product concept increases, while the possibilities of making changes on the concept decrease. For that reason, existing approaches describe integration points for product architecture design in different phases of the design process, depending on the information required and possibilities remaining for making specific product architecture decisions. However, in many cases in industrial practice, it can be observed that the product architecture is considered late in the process on the basis of product concepts of high maturity [ASS+09:242] [Kip12:61]. Therefore, some approaches aim at shifting decisions on the product architecture to early phases of the design process in order to increase the possibilities of influence on constitutional product properties [Deu15:18]. Nevertheless, later iterations will be necessary in order to revise decisions when more information about the product concepts are available [CWE+04:4]. Thus, in general, it is crucial to start initiating and planning considerations of the product architecture at an early points in time of the design process when possibilities of influence are still high.

Factor E3: Continuity of product architecture consideration: As stated before, the consideration of a most suitable point in time for a design decision depends, first, on the available information, and second, on the possibility to influence the product concept. Due to the resulting conflicting situation, a central challenge for the organization of design processes is to ensure a continuity of product architecture consideration [Deu15:161] [Zie12:66ff.] [Wie02:4]. Therefore, designers must be enabled to coordinate iterations while applying different approaches for product architecture design [Ble11:19], for instance, by allowing to use product models of different concretization at different points in time and consider transitions between product models [Kip12:96]. Thus, it is not possible to define specific points in time to integrate product architecture design within a design process. Instead, it is necessary to establish design processes in which a continuity of consideration is possible and different methods can be arranged and combined by the designers [Deu15:18].

C Case studies for problem clarification

Table C.1: Case studies for problem clarification

ID	Project aim	Type of company	Role of author in project
P1	Elaborating concepts for integration of additional functionality into existing product with a focus on reducing size, reducing weight, and increasing aesthetic appearance	Automotive supplier	Supervision of MA thesis (1/2 year)
P2	Analyzing product portfolio regarding existing product variety and elaborating new modularization concepts with a focus on reducing production cost, allowing fast configuration, and allowing fast tender processes	Plant manufacturer	Bilateral cooperation (1 year)
P3	Elaborating new concepts for retrofit parts with a focus on increasing the variety of products (required by the variety of original vehicles), improving partner communication, and reducing efforts for testing	Utility vehicles supplier	Bilateral cooperation (5 years)
P4	Analyzing product portfolio regarding future developments on markets and elaborating new concepts with a focus on increasing variety of products, ensuring independence of partners, and allowing fast tender processes	Utility vehicles supplier	Bilateral cooperation (1/2 year)
P5	Analyzing development processes in interdisciplinary environments with a focus on increasing flexibility to react to market changes, improve process organization, and improving responsiveness to changes	Automotive OEM	Bilateral cooperation (2 years)
P6	Analyzing product portfolio regarding existing product variety and elaborating new modularization concepts considering the whole life cycle with a focus on improving knowledge management and improving organization processes	Machine manufacturer	Bilateral cooperation (1/2 year)
P7	Elaborating concepts for mechanical assemblies considering potentials of additive manufacturing with focus on increasing functionality, cost reduction, and weight/size reduction	Automotive OEM	Bilateral cooperation (2 years)

D Overview of analyzed PAD approaches

In order to derive knowledge related to product architecture design to be integrated as knowledge elements into the framework, various established approaches from literature were analyzed. The following table lists the analyzed approaches and shows to which knowledge elements a contribution could be identified.

Table D.1: Analyzed examples of PAD approaches analyzed regarding the five hypotheses

Approach	**Source**	**Contrib. to hyp.**				
		1	**2**	**3**	**4**	**5**
Approach for Established Architecture	[UE12:187ff.]	◐	○	●	◐	◐
Approach for Function Integration	[Zie12:154ff.]	◐	◐	●	●	●
Benefits of Modularity	[GPZ03:295ff.]	○	○	◐	○	○
Change Model & Effect Analysis	[RVC+03:2ff.]	○	○	◐	○	◐
Concept Opportunity Diagrams	[KWJ+10:3ff.]	◐	○	○	◐	◐
Developing Flexible Products for Changing Environments	[Bis10:83]	◐	○	◐	●	○
Development of Product Platforms	[Bor61:45ff.]	◐	○	◐	◐	◐
Design for Transformation	[SSK+09:3ff.]	○	○	◐	◐	◐
Design for Variety	[MI02:214ff.]	◐	○	◐	◐	◐
Designing Product Archit. / Archit. Workframe	[Wie02:114ff.]	●	◐	◐	◐	◐
Developm. of Change-robust Platform Archit.	[Bau16:109ff.]	◐	◐	◐	●	◐
Function-oriented Platform Development	[Ren07:100ff.]	◐	◐	●	●	◐
Function Based Approach for Product Integration	[KL11:3ff.]	◐	○	○	◐	◐
Function Designs of Parts and Assemblies	[Kol98:307]	○	○	◐	◐	○
Function Integration and Separation	[KG03:217ff.]	◐	○	◐	◐	◐
Function Sharing in Mechanical Design	[US90:342ff.]	◐	○	◐	◐	◐
Generic Approach of Modularization[14]	[KG18:130ff.]	◐	○	◐	◐	●
High-definition Design Struct. Matrix Approach	[TSW12:15ff.]	◐	○	○	◐	◐
Implication of Product Architecture on the Firm	[YW07:118ff.]	○	○	●	◐	○
Integration Analysis of Product Decomposition	[PE94:3ff.]	◐	○	◐	◐	◐
Method for Devel. Assembly-oriented Product Structures[15]	[Hal14:81ff.]	◐	◐	◐	●	◐
Method for Developing Modular Product Families[15]	[Ble11:65ff.]	●	◐	●	◐	◐
Method of Variety-oriented Product Design[15]	[Kip12:73ff.]	●	●	◐	●	◐
Method of Module Heuristics	[Sto97:46ff.]	◐	◐	○	◐	◐

Tab. D.1: Analyzed examples of PAD approaches analyzed regarding the five hypotheses (continued)

Modular Design in Life Cycle Design	[UFT+08:1ff.]	◐	○	◐	◐	◐
Modular Product Development	[PBF+07:499ff.]	●	◐	◐	◐	●
Modular Function Deployment	[Eri98:72ff.]	◐	○	●	◐	●
Modular Platform Definition Process	[OHS+16:2ff.]	●	◐	◐	○	●
Modular Product Development	[Göp98:112ff.]	◐	○	●	◐	◐
Product Architecture Assessment	[Fix05:351ff.]	◐	○	●	◐	◐
Product Design for the Life Cycle	[NBR98:1ff.]	◐	○	◐	◐	◐
Product Family Master Plan	[Har06:81ff.]	●	◐	◐	◐	◐
Product System Modularity Construct	[Sal07:219ff.]	○	○	◐	●	○
Reduction and Separation of Structure Graphs	[Bir80:60ff.]	◐	○	○	◐	○
Simplification of Design	[Rod76:272ff.]	◐	○	◐	◐	◐
Strategy of the One-part Machine	[EKL+14:329]	◐	○	◐	◐	●
Systematic Approach for Function Integration	[Rot00:245]	◐	◐	◐	●	◐
Systematic Approach to the Development and Design of Technical Systems and Products	[VDI93:6ff.]	◐	◐	◐	◐	○
Variety-optimizing Product Design	[Fir03:40ff.]	●	●	◐	◐	●
Variety-oriented Design	[Cae91:48ff.]	●	◐	◐	◐	◐

Legend: ● ≙ approach provides meta structure, ◐ ≙ approach provides single elements, ○ ≙ no contribution

[14] Approach is considered independently from the *Integrated PKT Approach* [KG18:208ff.], see Sec. 2.7.3, that is mentioned in the same literature source.

[15] Approach is part of the *Integrated PKT Approach* [KG18:208ff.], see Sec. 2.7.3. The parts are listed separately in order to distinguish their different focus.

E Detailed description of systematized knowledge elements

E.1 PA representations

In Sec. 5.2.3, PA representations are described as one type of knowledge element that are included in the tool. Tab. E.1 gives an overview of all PA representations included in the tool at the time of publishing this work. Beside the here shown allocation to PA levels, further allocation, for instance, to PAD goals are stored in the database that cannot be outlined here due to limitations of space.

Table E.1: Collection of PA representations in database

#	Representation	Literature	PA levels				
			F	E	W	B	M
R1	Architecture Graph Representation	[Bau16:156ff.]	○	○	○	●	●
R2	Architecture Workframe	[Wie02:129ff.]	●	○	○	◐	●
R3	Domain-oriented Function Structure	[Jan06:2f.]	●	○	○	○	○
R4	Flow-oriented Function Structure	[Sto97:46f.]	●	○	○	○	○
R5	Generic Organ Diagram	[Har06:100ff.]	●	○	○	○	◐
R6	Geometric (Working) Structure	[Rot00:237ff.]	○	○	●	○	○
R7	Integrated Product and Assembly Structure[16]	[Hal14:93ff.]	○	○	○	○	●
R8	METUS Diamond	[Göp98:256ff.]	◐	○	○	◐	●
R9	Modular Products Systematics	[PBF+07:496ff.]	◐	○	○	○	●
R10	Module Interface Graph[16]	[Ble11:75ff.]	◐	○	○	●	●
R11	Module Process Chart[16]	[Ble11:65ff.]	○	○	○	◐	●
R12	Product Architecture Scheme	[Ulr95:420ff.]	◐	○	○	◐	●
R13	Product Family Function Structure[16]	[Ble11:72ff.]	●	○	○	○	○
R14	Product Family Master Plan	[Har06:106ff.]	●	○	○	●	◐
R15	Solution-function Matrix	[KG03:217ff.]	◐	●	◐	○	○
R16	Structure Graph with Working Surface Couplings	[Bir80:61ff.]	○	○	●	○	○
R17	Tree of (external) Variety[16]	[Kip12:81ff.]	○	○	○	○	◐
R18	Variety Allocation Model[16]	[Kip12:73ff.]	●	◐	●	●	○
R19	Variety Tree	[Cae91:48ff.]	○	○	○	●	○

Legend: ● ≙ main focus, ◐ ≙ side focus, ○ ≙ not addressed

[16]Approach is part of the *Integrated PKT Approach* [KG18:208ff.], see Sec. 2.7.3. The parts are listed separately in order to distinguish their different PA representations.

E.2 PAD goals

In Sec. 5.4.3, PAD goals are described as one type of knowledge element that are included in the tool. The *PAD Goal Chart* in Fig. E.1 as well as Tab. E.2 gives an overview of all PAD goals included in the tool at the time of publishing this work. besides the classification of the goals, the table provides short descriptions of the goals. The goals are clustered according to the strategic goals as described in Sec. 5.4.2. From this systematization approaches result the number of 9x3=27 PAD goals.

It shall be highlighted that the PAD goals given here are only such design goals that are related to product architecture. Within real design situations, further design goals can possibly relevant. The here presented list of PAD goals only claims to be used for goal clarification regarding product architecture design.

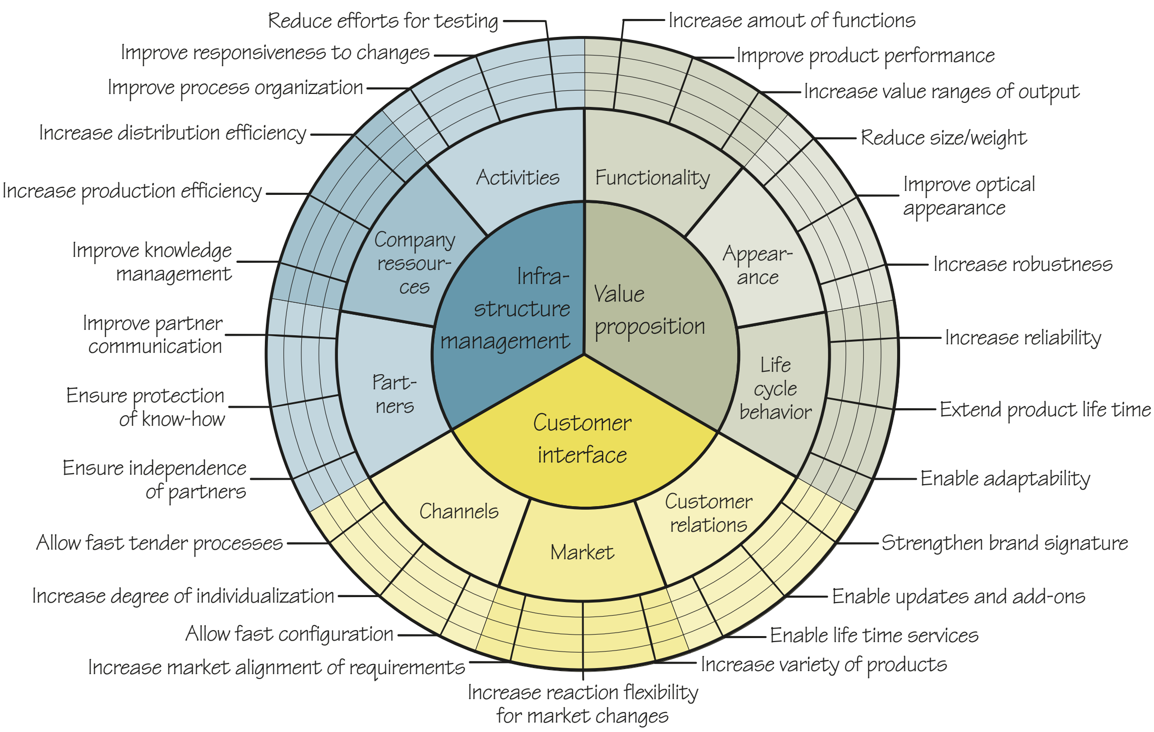


Figure E.1: PAD Goal Chart

Table E.2: PAD goals in database

#	PAD goal	Description	Literature
Functionality			
G1	Increase amount of functions	The number of functions that a product or a component can fulfill, which can be increase, for instance, by function integration.	[Zie12:156] [Kol98:211]

Tab. E.2: PAD goals in database (continued)

G2	Improve product performance	The quality of the fulfillment of functions. By product architecture design, for instance, the number of separated parts within chains of power transmission can be reduced that may decrease the product performance due to friction losses.	[Zie12:162]
G3	Increase value range of output	The defined scope of value ranges of the output within that the functions of a product are fulfilled, e.g., the throughput of material. High value ranges can be achieved, for instance, when variants of product or parts are consolidated.	[Ren07:130] [KL14:1]
Appearance			
G4	Reduce size/weight	The required building space of a part, the size of product, and the often related weight of the product. For instance, integral design can allow to reduce size and weight when a reduced number of parts fulfills the same amount of functions.	[GK08:201] [Zie12:159,160] [EKL+14:328]
G5	Improve optical appearance	The optical appearance of a product influencing the aesthetic and functional perception of the product. Separations of parts at designated locations can, for instance, enhance the recognition of functional surfaces.	[Eri98:74] [Zie12:222]
G6	Increase robustness	The robustness of a part or product in terms of resistance against physical damage. In some cases, an integral design can increase the robustness due to a reduced number of fault-prone intersections between parts.	[Ere96:235]
Life cycle behavior			
G7	Increase reliability	The reliability of a product in terms of its ability to fulfill the required functions when needed. The reliability can be increased, for instance, by the use of common parts tried and tested in many product variants and/or generations.	[Ren07:118] [Zie12:164]
G8	Extend product life time	The life time of the product being used by the customers. The life time can be increased by designing products either resistant against defects (e.g., by integral designs), or maintainable and recyclable (e.g., by modularity).	[UFT+08:1] [Zie12:162]
G9	Enable adaptability	The ability of the product to adapt to changed environments within use. Adaptability can be achieved, for instance, by allowing users to variate the product during use time by changing modules.	[UE12:187] [Ink16:21] [Bis10:31]
Customer relation			

Tab. E.2: PAD goals in database (continued)

G10	Strengthen brand signature	The recognition value of the product giving reliance on consistency of the brand of the company to customers. It can be strengthened, for instance, by using product modules over many product generations that haven been proven reliable for customers.	[Eri98:73] [YW07:125]
G11	Enable updates and add-ons	The possibility of a product to be changed during use-phase by updates (replacement of a part) and add-ons (extension of parts), which can be enabled, for instance, by separation of modules to be updated or extended.	[UFT+08:1] [Bis10:31] [Eri98:76] [UE12:187]
G12	Enable life time services	The possibility to offer after-sales services for products for maintenance and repair. The product architecture can facilitate those services, for instance, by anticipating wear-prone parts and separating them from the rest of the product as changeable modules.	[Eri98:76] [UE12:187] [Kol98:318] [UFT+08:1] [Kip12:76] [Fix05:348]
Market			
G13	Increase variety of products	The range of variants of products that a company can offer to customers. Product platforms, for instance, can allow companies to offer many product variants based on combinations of modules for deriving different product functionalities or dimensions.	[FHH+02:22] [Eri98:74] [UE12:188] [Kol98:318] [Kip12:76] [Ren07:118] [YW07:124]
G14	Increase reaction flexibility to market changes	The possibility of a company to react fast to changes on markets by offering new products or product variants. To increase the flexibility, companies can anticipate future changes on the product and modularize those parts that may be updated in next product generations.	[Bis10:40] [RVC+03:1] [Ren07:118] [Eri98:73] [YW07:131]
G15	Increase market alignment of requirements	The alignment of products to market demands by ordering the requirements to customer groups appropriately. By structuring the product portfolio as well as the product according to market demands, for instance, the overview of market requirements can be increased.	[YW07:125] [Fix05:348] [Ren07:118]
Channels			
G16	Allow fast configuration	The ability of a company to create product variants fast due to configuration. Product architecture design can facilitate the configuration, for instance, by defining standardized interfaces allowing efficient assembly of product variants.	[YW07:129] [Ren07:118] [FHH+02:15]

Tab. E.2: PAD goals in database (continued)

G17	Increase degree of individualization	The ability of a company to offer customers individualized products. For instance, modularity can allow to integrate customers-specific modules into products to meet the customers requirements accurately.	[YW07:129] [Fix05:348] [FHH+02:17]
G18	Allow fast tender processes	The ability of a company to handle orders fast from receiving inquiries, providing price information, and delivering the product. Product architecture allows to make these processes more efficient by setting up products on the basis of company-common structures with reusable modules.	[YW07:129] [Ren07:118]
Partners			
G19	Ensure independence of partners	The ability of a company to develop and manufacture products independently from partners. For instance, the assignment of only limited extends of the product to partners due to an appropriate modularization can preserve the control of a company.	[YW07:123] [Zie12:222] [Fix05:348]
G20	Ensure protection of know-how	The assurance of a company to protect company-intern know-how when cooperating with partners. The drawing of module boundaries at critical product extends can, for instance, limited the know-how accessible for partners.	[Zie12:222]
G21	Improve partner communication	The organization of communication structures with partners in development and products. For instance, clear defined interfaces between modules and reduced interdependencies of modules can decrease the communication effort.	[Ste81:71] [PE94:1] [Eri98:76] [UE12:191] [YW07:127] [Fix05:348]
Company resources			
G22	Improve knowledge management	The long-term assurance of conservation and development of the knowledge of a company. A clear structuring of the product in modules, for instance, can facilitate the storage and reuse of product related knowledge.	[YW07:123] [Ren07:118]
G23	Increase production efficiency	The efficiency of a company producing products, which mainly affects the total product cost. Product architecture allows to reduce cost, for instance, by reducing the internal variety of parts in products or by reducing the number of parts per product.	[Kip12:76] [Eri98:73,74] [Kol98:318] [Zie12:164,167] [YW07:129] [Fix05:348]

Tab. E.2: PAD goals in database (continued)

G24	Increase distribution efficiency	The efficiency of a company in distribution of products including warehousing, logistics, and installation of products. By considering the whole life-cycle of products, product architecture design can provide modules appropriate for storage and transport.	[Kip12:76] [YW07:129]
Activities			
G25	Improve process organization	The efficiency of communication processes within a company including development, production, and distribution. Product architecture design can affect the process organization, for instance, by contributing to a suitable breakdown structure of the product that allows teams of persons within a firm or suppliers to work on modules of the product independently of each other.	[Sto97:2] [Kip12:76] [Ren07:118] [YW07:127] [Fix05:348] [Ste81:71] [UE12:191] [PE94:1]
G26	Improve responsiveness to changes	The ability of a company to react to changes within the product creation process caused, e.g., by changed requirements on the product. For addressing this, modules prone to changes can be separated by interfaces from the rest of the product to be easily exchanged for updated modules.	[RVC+03:1] [Ren07:118] [YW07:130] [Bis10:31] [Eri98:73]
G27	Reduce efforts for testing	The efficiency of processes for testing the product prior to delivery. During product architecture design, for instance, modules can be anticipated that will be tested separately of each other.	[Eri98:75] [Ren07:118]

E.3 PAD principles

In Sec. 5.5.3, PAD principles are described as one type of knowledge element that are included in the tool. Tab. E.3 gives an overview of all PAD principles included in the tool at the time of publishing this work. Beside the here shown allocation to PA levels, further allocation, for instance, to PAD goals are stored in the database that cannot be outlined here due to limitations of space.

Table E.3: Collection of PAD principles in database

#	Principle	Literature	PA levels				
			F	E	W	B	M
1	Integrate design units by allowing for adjustable output parameters	[Bis10:218]	○	●	●	◐	○
2	Integrate design units by avoiding unnecessary partitions by using alternative manufacturing	[EKL+14:237]	○	○	◐	●	○
3	Integrate design units by increasing the number of working surfaces	[Rot00:272]	○	○	●	○	○
4	Integrate design units by sharing mechanical supporting structures	[Rod76:272]	○	○	●	○	○
5	Integrate design units for avoiding expensive assembly	[Hal14:104]	○	○	○	●	●
6	Integrate design units for avoiding fault-prone assembly intersections	[Zie12:164]	○	○	○	◐	●
7	Integrate design units for avoiding interfaces at flows of forces	[Zie12:162]	○	○	●	◐	○
8	Integrate design units for avoiding interfaces with requirements on preciseness	[Zie12:163]	○	○	●	◐	○
9	Integrate design units into modules with strong interdependencies	[PE94:3]	●	○	○	○	●
10	Integrate design units of dependent variety	[Kip12:102]	○	○	◐	●	○
11	Integrate functions for compensating negative functions	[Zie12:163]	●	◐	○	○	○
12	Integrate new functions by exploitation of existing capabilities	[KG03:223]	●	●	○	○	○
13	Integrate new functions by extending capabilities	[Zie12:38]	○	○	○	●	○
14	Integrate new functions by temporal switching modes	[Ink16:120]	●	○	●	○	○
15	Integrate standard modules into a platform	[PD99:201]	○	○	○	○	●
16	Integrate variant or optional design units into few assembly modules	[Hal14:90]	○	○	○	○	●

Table E.3: Tab. E.3: Collection of PAD principles in database (continued)

17	Separate design units according to demanded configurability	[Ren07:138]	○	○	○	○	●
18	Separate design units according to documentation	[YW07:123]	○	○	○	○	●
19	Separate design units according to functional autonomous chunks	[Göp98:104]	●	○	○	○	●
20	Separate design units according to separate testability	[Eri98:75]	○	○	○	○	●
21	Separate design units assigned to partners	[Eri98:76]	○	○	○	○	●
22	Separate design units being possible subject to technological push	[Wie02:111]	○	○	○	○	●
23	Separate design units being possible subject of design changes	[Bau16:291]	○	○	○	○	●
24	Separate design units by differentiating sectors demanding different production quality	[Zie12:222]	○	○	○	●	○
25	Separate design units by differentiating standard and variant sections	[Kip12:98]	○	○	●	◐	○
26	Separate design units for achieving redundancies	[Bis10:219]	●	●	◐	◐	○
27	Separate design units for allowing for adjustment	[Zie12:224]	○	○	○	●	○
28	Separate design units for allowing pre-assembly	[EKL+14:287]	○	○	○	○	●
29	Separate design units for changeability for upgrades	[Bis10:219]	○	○	○	○	●
30	Separate design units for highlighting aesthetic dimensions	[Heu04:41]	○	○	○	●	◐
31	Separate design units for independent testing	[Eri98:75]	○	○	○	○	●
32	Separate design units for individual styling	[Eri98:74]	○	○	○	○	●
33	Separate design units of simple and complex assembly	[Hal14:90]	○	○	○	○	●
34	Separate design units to reduce risk of complete product failure	[Bis10:214]	○	○	○	●	●
35	Separate design units when included knowledge needs to be protected	[Zie12:222]	○	○	○	○	●
36	Separate different domains for parallel development	[Jan06:29]	●	◐	○	○	◐
37	Separate fast wearing design units for replacement	[Wie02:111]	○	○	○	◐	●
38	Separate functional chunks according to a branching flow	[Sto97:58]	●	○	○	○	○
39	Separate functional chunks according to the dominant flow	[Sto97:47]	●	○	○	○	○
40	Separate functions by postponing those of different configuration characteristics	[Kip12:112]	●	○	○	○	○

Table E.3: Tab. E.3: Collection of PAD principles in database (continued)

41	Separate functions of different configuration characteristics	[Kip12:98]	●	○	○	○	○
42	Separate generation constituting modules	[Eri98:73]	○	○	○	○	●
43	Standardize design units according to market standards	[EKL+14:318]	○	○	○	●	●
44	Standardize design units by generating variety by varied working principles instead of different effects	[Kip12:106]	○	●	◐	○	○
45	Standardize design units by harmonization of input values/flows	[Kip12:113]	●	○	○	○	○
46	Standardize design units by oversizing for use in product variants	[HK17:153]	○	○	◐	●	○
47	Standardize design units with high development expenses to be used in other products	[MI02:214]	○	○	○	○	●
48	Standardize interfaces of design units being possible subject of design changes	[Wie02:111]	○	○	○	◐	●
49	Standardize interfaces of design units with high assembly affort	[Bis10:217]	○	○	○	○	○
50	Standardize similar design units by harmonization	[Ren07:130]	◐	◐	◐	●	◔
51	Standardize unfavorable stocking parts	[FG13:840]	○	○	○	○	●
52	Variate design units by allowing scalability by the user	[Ink16:22]	○	◐	●	◐	○
53	Variate products by allowing up-scaling by combination of multiple modules of same kind	[Bis10:214]	○	○	○	○	●
54	Variate products by configuration of software instead of hardware	[Bau16:292]	○	●	○	○	○
55	Variate products by different order or mode of assembly	[Bis10:215]	○	○	◐	●	○
56	Variate products by sectional configuration of modules	[PD99:201]	○	○	○	○	●
57	Variate products by serial configuration of modules	[PD99:201]	○	○	○	○	●

Legend: ● ≙ main focus, ◐ ≙ side focus, ○ ≙ not addressed

E.4 PAD methods

In Sec. 5.6.3, PAD methods are described as one type of knowledge element that are included in the tool. Tab. E.4 gives an overview of all PAD methods included in the tool at the time of publishing this work. Beside the here shown allocation to the four activities of the *Basic PAD Method*, further allocation, for instance, to PAD goals are stored in the database that cannot be outlined here due to limitations of space.

Table E.4: Collection of PAD methods in database

#	Method	Literature	Activities			
			Clarifying PAD goals	Generating PA representations	Analyzing/ Synthesizing the PA	Evaluating PA concepts
M1	Architecture Design Method	[Wie02:114ff.]	○	●	●	○
M2	Business Process Modeling	[VHS15:18ff.]	●	◐	○	○
M3	Change Mode & Effect Analysis	[RVC+03:2ff.]	○	◐	◐	●
M4	Developing Flexible Products for Changing Environments	[Bis10:83ff.]	○	○	●	○
M5	Development of Change-robust Platform Architectures	[Bau16:109ff.]	●	●	●	○
M6	Function Integration and Separation	[KG03:217ff.]	○	●	●	○
M7	Function-oriented Platform Development	[Ren07:100ff.]	●	◐	◐	◐
M8	Generic Approach for Modularization[17]	[KG18:130ff.]	◐	●	●	○
M9	Integrated PKT Approach for Developing Modular Product Families	[KG18:208ff.]	●	●	●	●
M10	Integration Analysis of Product Decomposition	[PE94:3ff.]	○	◐	●	●
M11	Method for Developing Assembly-oriented Product Structures[17]	[Hal14:81ff.]	◐	●	●	●
M12	Method for Developing Modular Product Families[17]	[Ble11:65ff.]	●	●	◐	●
M13	Method of Module Heuristics	[Sto97:46ff.]	○	●	●	○
M14	Method of Variety-oriented Product Design[17]	[Kip12:73ff.]	◐	●	●	●
M15	Modular Design in Life Cycle Design	[UFT+08:1ff.]	◐	●	◐	○

Table E.4: Tab. E.3: Collection of PAD methods in database (continued)

M16	Modular Function Deployment	[Eri98:72ff.]	●	◐	◐	●
M17	Modular Product Development	[PBF+07:499ff.]	◐	●	●	◐
M18	Product Family Master Plan	[Har06:81ff.]	○	●	◐	●
M19	Systematic Approach for Function Integration	[Rot00:245ff.]	○	●	●	○

Legend: ● $\widehat{=}$ main focus, ◐ $\widehat{=}$ side focus, ○ $\widehat{=}$ not addressed

[16] Approach is considered independently from the *Integrated PKT Approach* [KG18:208ff.], see Sec. 2.7.3, that is mentioned in the same literature source.

[17] Approach is part of the *Integrated PKT Approach* [KG18:208ff.], see M9. The parts are listed separately since they include independently used methods with steps with different focus.

E.5 Mapping of PAD goals and PA levels

The following table shows correlations between PAD goals and PA levels in order to enable designers to identify those PA levels that are appropriate for addressing specific PAD goals.

The correlations are determined based on PAD principles (see Sec. 5.5.3 and Tab. E.3). Within the database, each principle is corrleated to all 27 PAD goals. Moreover, for each principle, it is indicated on which PA level it can be applied. By calculating the maximum corrlelation between a PA level and a PAD goal, the values shown in the following table are determined.

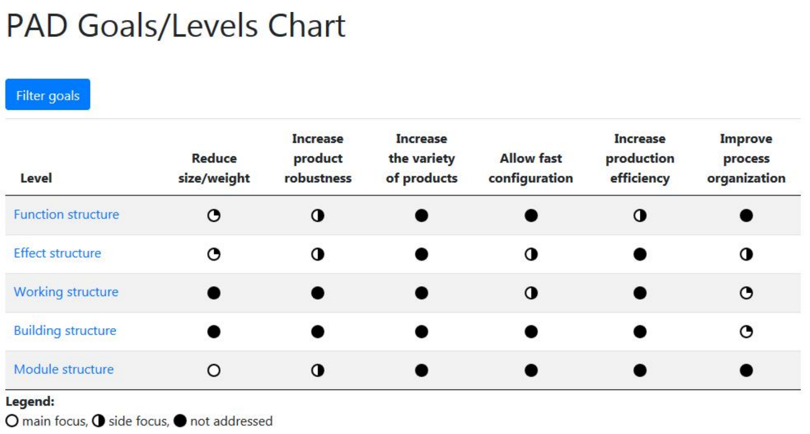
Since the number of PAD principles is limited to the review of a limited number of literature sources, obviously, this table includes a finding that can be refined by further research. Moreover, the evaluation of the correlations of the PAD principles with PAD goals and PA levels is based on the author's subjective assessment. Further research can refine the results based on the existing database.

Table E.5: Mapping of PAD goals to PA levels

PA level	**Increase amount of functions**	**Improve product performance**	**Increase value range of output**	**Reduce size/weight**	**Improve optical appearance**	**Increase robustness**	**Increase reliability**	**Extend product life time**	**Enable adaptability**	**Strengthen brand signature**	**Enable updates and add-ons**	**Enable life time services**	**Increase variety of products**	**Increase flexibility for market changes**	**Increase the order of requirements**	**Allow fast configuration**	**Increase degree of individualization**	**Allow fast tender processes**	**Ensure independence of partners**	**Ensure protection of know-how**	**Improve partner communication**	**Improve knowledge management**	**Increase production efficiency**	**Increase distribution efficiency**	**Improve process organization**	**Improve responsiveness to changes**	**Reduce efforts for testing**
Function structure	●	●	◐	◔	○	◐	●	◐	●	○	◐	○	●	◐	◐	●	○	○	◐	○	◐	●	◐	◐	●	◐	◐
Effect structure	●	◐	●	◔	○	◐	●	◐	●	○	◐	○	●	◔	◐	◐	◐	○	○	○	○	◐	●	○	◐	◐	○
Working structure	●	●	●	●	○	●	◐	◐	●	○	◐	○	●	◐	◐	◐	◐	◔	○	○	○	◐	●	◐	◐	◔	○
Building structure	●	◐	◐	●	●	●	●	◐	●	○	◐	●	●	◐	●	●	◐	◔	●	○	○	◐	●	◐	◔	◐	◐
Module structure	○	○	○	○	◐	◐	●	◐	○	●	●	●	●	●	◐	●	●	◐	●	●	●	●	●	●	●	●	●

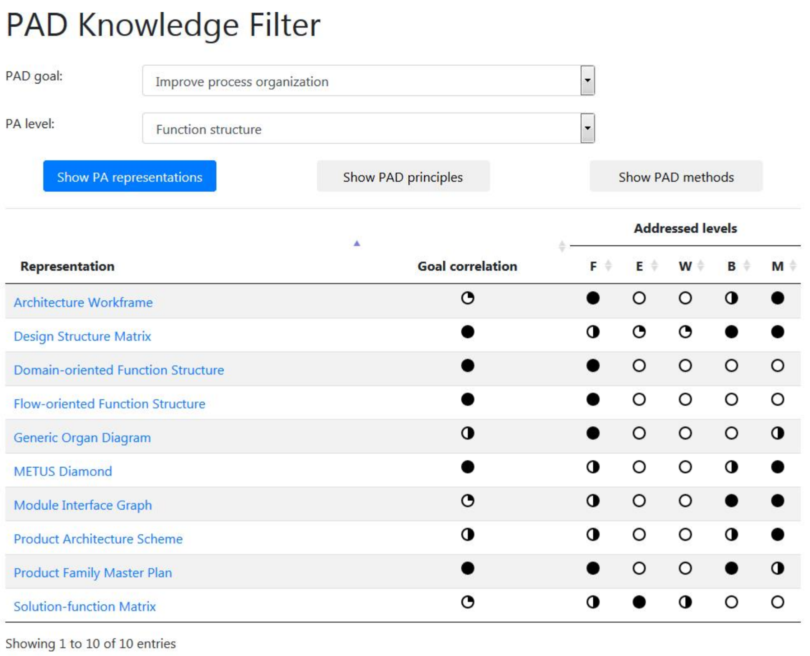
Legend: ● ≙ very strong correlation, ◕ ≙ strong correlation, ◐ ≙ medium correlation, ◔ ≙ weak correlation, ○ ≙ no correlation

F Exemplary views of the software demonstrator



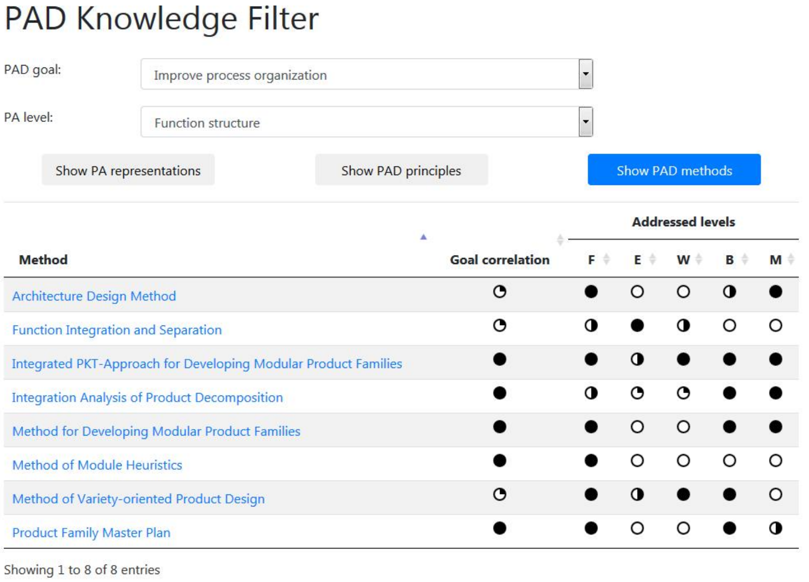
Level	Reduce size/weight	Increase product robustness	Increase the variety of products	Allow fast configuration	Increase production efficiency	Improve process organization
Function structure	◔	◑	●	●	◑	●
Effect structure	◔	◑	●	◑	●	◑
Working structure	●	●	●	◑	●	◔
Building structure	●	●	●	●	●	◔
Module structure	○	◑	●	●	●	●

Figure F.1: Screenshot of an exemplary filter view on *PAD Goals/Levels Chart*



Representation	Goal correlation	Addressed levels: F	E	W	B	M
Architecture Workframe	◔	●	○	○	◑	●
Design Structure Matrix	●	◑	◔	◔	●	●
Domain-oriented Function Structure	●	●	○	○	○	○
Flow-oriented Function Structure	●	●	○	○	○	○
Generic Organ Diagram	◑	●	○	○	○	◑
METUS Diamond	●	◑	○	○	◑	●
Module Interface Graph	◔	◑	○	○	●	●
Product Architecture Scheme	◑	◑	○	○	◑	●
Product Family Master Plan	●	●	○	○	●	◑
Solution-function Matrix	◔	◑	●	◑	○	○

Figure F.2: Screenshot of an exemplary filter view on PA representations for the goal *improving process organization* on the level of the *function structure*


PAD Knowledge Filter

PAD goal: Improve process organization

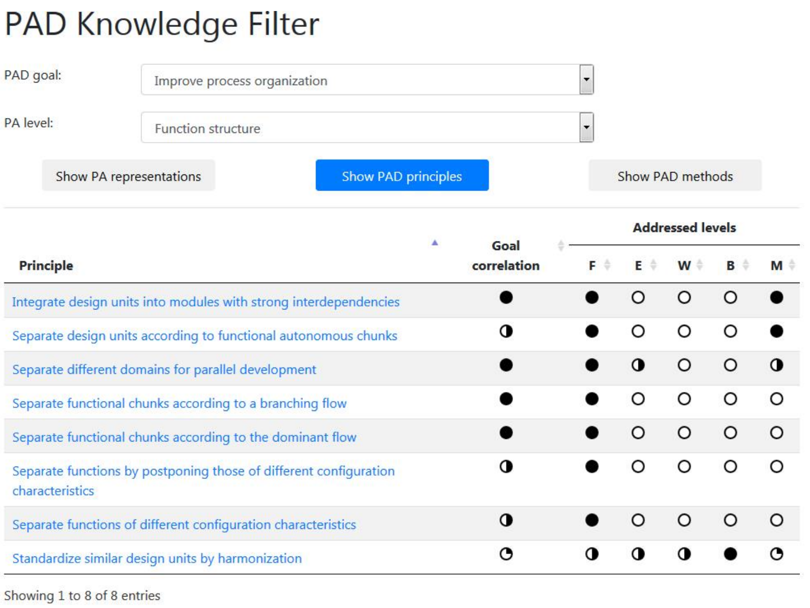
PA level: Function structure

Show PA representations | Show PAD principles | Show PAD methods

Method	Goal correlation	Addressed levels: F	E	W	B	M
Architecture Design Method	◔	●	○	○	◑	●
Function Integration and Separation	◔	◑	●	◑	○	○
Integrated PKT-Approach for Developing Modular Product Families	●	●	◑	●	●	●
Integration Analysis of Product Decomposition	●	◑	◔	◔	●	●
Method for Developing Modular Product Families	●	●	○	○	●	●
Method of Module Heuristics	●	●	○	○	○	○
Method of Variety-oriented Product Design	◔	●	◑	●	●	○
Product Family Master Plan	●	●	○	○	●	◑

Showing 1 to 8 of 8 entries

Figure F.3: Screenshot of an exemplary filter view on PAD methods for the goal *improving process organization* on the level of the *function structure*


PAD Knowledge Filter

PAD goal: Improve process organization

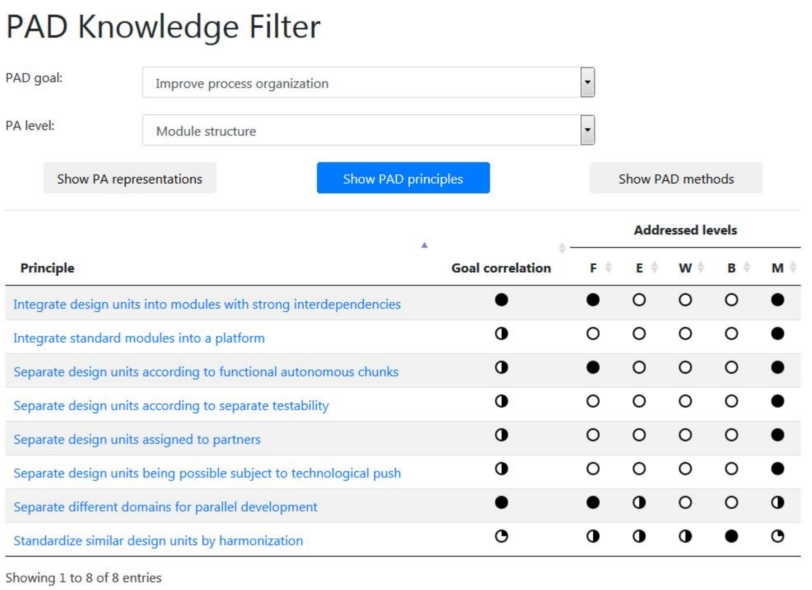
PA level: Function structure

Show PA representations | Show PAD principles | Show PAD methods

Principle	Goal correlation	Addressed levels: F	E	W	B	M
Integrate design units into modules with strong interdependencies	●	●	○	○	○	●
Separate design units according to functional autonomous chunks	◑	●	○	○	○	●
Separate different domains for parallel development	●	●	◑	○	○	◑
Separate functional chunks according to a branching flow	●	●	○	○	○	○
Separate functional chunks according to the dominant flow	●	●	○	○	○	○
Separate functions by postponing those of different configuration characteristics	◑	●	○	○	○	○
Separate functions of different configuration characteristics	◑	●	○	○	○	○
Standardize similar design units by harmonization	◔	◑	◑	◑	●	◔

Showing 1 to 8 of 8 entries

Figure F.4: Screenshot of an exemplary filter view on PAD principles for the goal *improving process organization* on the level of the *function structure*



PAD Knowledge Filter

PAD goal: Improve process organization

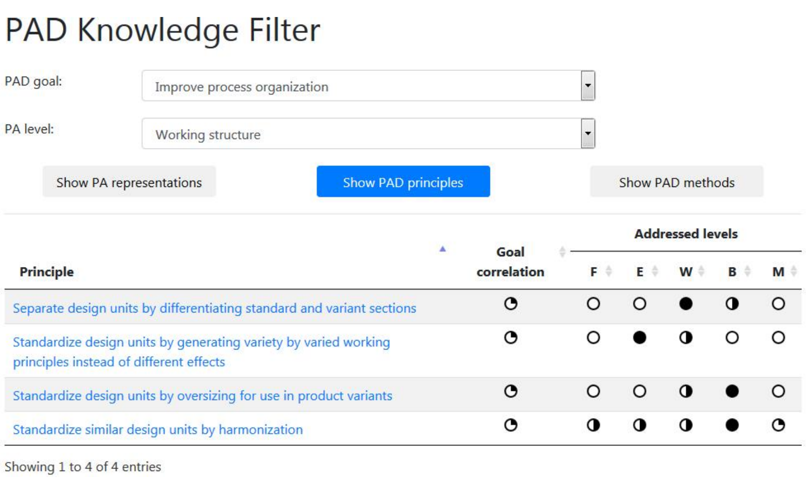
PA level: Module structure

Show PA representations | Show PAD principles | Show PAD methods

Principle	Goal correlation	F	E	W	B	M
		Addressed levels				
Integrate design units into modules with strong interdependencies	●	●	○	○	○	●
Integrate standard modules into a platform	◑	○	○	○	○	●
Separate design units according to functional autonomous chunks	◑	●	○	○	○	●
Separate design units according to separate testability	◑	○	○	○	○	●
Separate design units assigned to partners	◑	○	○	○	○	●
Separate design units being possible subject to technological push	◑	○	○	○	○	●
Separate different domains for parallel development	●	●	◑	○	○	◑
Standardize similar design units by harmonization	◔	◑	◑	◑	●	◔

Showing 1 to 8 of 8 entries

Figure F.5: Screenshot of an exemplary filter view on PAD methods for the goal *improving process organization* on the level of the *module structure*



PAD Knowledge Filter

PAD goal: Improve process organization

PA level: Working structure

Show PA representations | Show PAD principles | Show PAD methods

Principle	Goal correlation	F	E	W	B	M
		Addressed levels				
Separate design units by differentiating standard and variant sections	◔	○	○	●	◑	○
Standardize design units by generating variety by varied working principles instead of different effects	◔	○	●	◑	○	○
Standardize design units by oversizing for use in product variants	◔	○	○	◑	●	○
Standardize similar design units by harmonization	◔	◑	◑	◑	●	◔

Showing 1 to 4 of 4 entries

Figure F.6: Screenshot of an exemplary filter view on PAD methods for the goal *improving process organization* on the level of the *working structure*

List of publications

Throughout the elaboration of this thesis intermediate results were published in following papers and book chapters:

[GST+13] M. Gäde, M. Schönemann, E. Türck, T. Richter, C. Herrmann, T. Spengler, and T. Vietor. "Synergien in der kooperativen Produktentstehung. Hemmnisse und Potenziale im Entstehungsprozess mechatronischer Produkte". In: *Zeitschrift für wirtschaftlichen Fabrikbetrieb* 108 (12 2013), pp. 2–6.

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Technische Universität Braunschweig
Institut für Konstruktionstechnik
Prof. Dr.-Ing. Thomas Vietor
Langer Kamp 8
38106 Braunschweig
Telefon +49 531 391-3343
Telefax +49 531 391-4572
konstruktionstechnik@tu-braunschweig.de
www.tu-braunschweig.de/ik

Technische Universität Braunschweig
Institut für Konstruktionstechnik
Prof. Dr.-Ing. Thomas Vietor
Langer Kamp 8
38106 Braunschweig
Telefon +49 531 391-3343
Telefax +49 531 391-4572
konstruktionstechnik@tu-braunschweig.de
www.tu-braunschweig.de/ik